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QUASI-CONTINUOUS EXPLOSIVE CONCEPTS FOR HARD ROCK EXCAVATION

Nikolai A. Louie

Shock Hydrodynamics

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FINAL REPORT

JUNE 1973

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13. ABSTRACT

The use of continuous or quasi-continuous systems for pulsed explosion rock excavation, can have major advantages over conventional methods. This report considers the feasibility and applicability of such an explosive system concept. The optimum properties of the explosive system, the effectiveness of the explosive rock interactions and the interactions between successive explosions were determined in tests on granite and concrete. A prototype multiple charge launcher was designed, built and tested to demonstrate the feasibility of a multiple feed system. The quasi-continuous explosive projectile launcher appears to be capable of unusually high drilling rates into hard rock. Recommendations are made for application of the launcher system to actual hard rock excavation conditions.

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Granite	1	3			
Concrete	1	3			

SUMMARY

The use of continuous or quasi-continuous systems for pulsed explosion rock excavation, can have major advantages over conventional methods. This report considers the feasibility and applicability of such an explosive system concept. The optimum properties of the explosive system, the effectiveness of the explosive-rock interactions, and the interactions between successive explosions were determined in tests on granite and concrete. A prototype multiple charge launcher was designed, built and tested to demonstrate the feasibility of a multiple feed system. The quasi-continuous explosive projectile launcher appears to be capable of unusually high drilling rates into hard rock. Recommendations are made for application of the launcher system to actual hard rock excavation conditions.

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1. INTRODUCTION

Continuous-feed explosive systems, or quasi-continuous systems such as closely-spaced pulsed explosion methods, could have major advantages over conventional drill-and-blast methods. In addition to operational advantages (especially in conjunction with continuous material handling techniques), such an explosive system could permit an extremely high energy flux at the working face, as well as a high degree of control of the localized application of the energy.

During this program, a quantitative, experimental study was made to evaluate the feasibility and possible utility of a quasi-continuous hard rock excavation system. The system concept is based on pulsed explosions obtained by successively projecting small explosive charges in a closely-spaced train against the rock face.

The objectives of the research were to determine

a. the effectiveness of quasi-continuously-fed explosive trains in causing fracture and removal of hard rock

b. the mechanisms which operate in such a process, and the effect of major parameters upon these mechanisms

c. the feasibility and probable utility of implementing quasi-continuous explosive processes into a system for excavation in hard rock

The approach taken primarily consisted of critical experiments designed to explore the basic questions regarding concept feasibility. It is considered that the most important questions have to do with the effectiveness of pulsed explosions on the rock face in breaking out and removing rock. In addition to the basic experiments, conceptual design studies were conducted to determine possible ways to implement pulsed explosion processes into a system for continuous hard rock excavation.

Experiments were run to evaluate the effectiveness of pulsed explosions, including single and multiple-charge firings. Both static experiments (where charges are emplaced on the rock face before firing) and dynamic experiments (where charges are gun-accelerated against the rock face) were carried out. Comparisons were made to determine relative effectiveness under various conditions, and to establish the mechanisms by which multiple charges fired at the same point operate to remove rock.

Information from these experiments, combined with design concepts for pulsed explosive systems, were used to estimate rock removal rates.

Recommendations are included at the close of this report regarding methods to further extend the promising results obtained.

2. DETONATION STUDIES

A prerequisite condition for employing a continuous or quasi-continuous feed, explosive, hard rock excavation system is that the particular explosive system utilized must provide safe handling and reliable detonation at the rock surface. Two approaches were studied in the present program, both related to the use of a small explosive projectile that would detonate from high velocity impact on the rock surface. The first approach was an investigation of the feasibility of obtaining the desired properties by a projectile containing sensitised secondary explosive. The second approach was the combination of an unsensitized secondary explosive with a small detonator.

2.1 SENSITIZED EXPLOSIVE EXPERIMENTS

The dynamic experiments in the detonation studies were carried out with the use of a simple compressed gas actuated launch tube. The system consisted of a quick opening, solenoid-operated valve which vented a pressurized nitrogen gas resevoir into the launch tube, where it accelerated the explosive projectile down a 20 ft. long tube. Velocities of 800-1000 feet per second for the explosive projectile were achieved using 200 PSIG resevoir pressure. The velocities were measured by means of two sets of electrical contact switches projecting a short distance into the barrel. As the thin aluminum projectile case struck the contact switches, an R-C discharge circuit was activated and the transit time between the two sets of switches were displayed on a time interval counter.

A projectile size of .75 inches was settled on early in the program. The criterion applied to this selection was the smallest size that would reliably propagate a detonation. Plate dent tests for various size cylinders of C-4 and Octol explosives initiated with an #8 detonator showed that a .75-inch diameter cylinder represented a minimum size. Use of a minimum size was desirable since this would minimise hazard to equipment and personnel, simplify the construction of test apparatus, and minimise the size of target blocks required. The standard projectile consisted of a .75-inch diameter x .75-inch-high x 10-12 mil thick aluminum cup filled with the explosive charge. The cup was projected with the open end in front.

An examination of published research and some personal contacts, related to unpublished research into impact detonation of pure secondary explosives in the 1000 fps range, indicated that obtaining reliable detonations for the projectiles was unlikely. The impact detonation of a secondary explosive in this velocity range is a very complex process, where the shock heating and the frictional heating during deformation and fracture of the explosive combine to cause deflagration that can grow to detonation under suitable conditions.

Impacts at 1000 fps of the standard projectile cup filled with either Composition-B, Octol, or C-4 explosive gave no detonations in our tests. Even when the explosive filler was changed to C-4 with a .5-inch-diameter x .5-inch-thick pellet of Tetryl inserted in front of the C-4, no detonations were obtained either.

One method to increase the sensitivity of a secondary explosive is by adding small inclusions composed of a material with a density substantially differing from the explosive density. To utilize this phenomenom, hollow glass microballons were added at loadings of 17 and 35 percent by volume to melted Composition-B and Octol explosives and cast into the projectile cups. Steel inclusions were also arranged around the Tetryl pellet in the Tetryl-C-4 explosive configurations. Neither of these conditions produced detonations in the velocity range used.

In the light of these results, it appeared that to achieve detonation of an explosive charge by impact, it would be necessary either to appreciably increase the impact velocity or to utilize more sensitive explosives. These options were not attractive both by reason of delay of the rest of the program by a peripheral study, of perhaps unwarranted difficulty, or for reasons of safety related to the handling of more sensitive explosive.

2.2 PROJECTILES WITH DETONATORS

To circumvent the problems enumerated above, a projectile configuration was adopted which involved using a small electric detonator imbedded into the front of the explosive charge. The purpose was to provide a prepackaged, safe and relatively insensitive initiator, which would function on crushing. The initial firings with this design, with and without a small Tetryl pellet booster under the detonator, gave reliable detonations of the main explosive in the 800-1000 fps velocity range in both cases. In subsequent testing it was found that the Tetryl pellet did not have to be included as part of the configuration.

The use of the electric detonator initiator design quickly gave a projectile that would reliably detonate on impact in the 1000 fps velocity range, and permitted the program to proceed to other objectives. The safety aspects of this design are favorable in that only a small amount of more sensitive explosive is used in each projectile and this material is confined and protected by the sturdy detonator enclosure, giving a relatively stable initiator package. Also, since the detonator is small and imbedded in C-4 explosive, it is provided with additional protection from all directions other than the desired impact point. The detonator was obtained from a commercial source, which eliminated a development program and assured that a large number of similar units would be obtainable.

The ad hoc detonator initiation design is somewhat disadvantageous in that it reduces the high explosive volume somewhat, may provide an increased projectile cost, and complicates the impact kinetics but these factors were considered minor with respect to its advantages in permitting the key elements of the program to be carried out. It is not the method which would be used in further applications.

Test firings were made to evaluate the performance of three different types of detonators for impact on a .25-inch-thick steel plate at velocities of 900 fps or less. It was found that all detonators functioned at 900 fps. A lower velocity limit for one of the deonators was determined at approximately 500 fps. The other two types functioned well at this velocity, but one provided what appeared to be more complete detonation of the high explosive charge, as determined by the damage to the steel plate. A large supply of this type was obtained. It should be noted that, other than the above, no attempt was made to optimize

detonator characteristics, since such an effort would be very peripheral to the overall objectives. Hence some uncertainty relative to the design parameters of the detonator initiator portion of the projectile still exist. Any data relative to the sensitivity and effectiveness of the detonator package is given to provide general limits of applicability and usefulness for the particular detonator type used in the tests.

The detonator presently used in the dynamic tests was originally fabricated by the supplier as an electric detonator. It is closed at one end by a plastic plug through which 2 or 3 wires project. This end will be referred to as the "wire end." The other end is the flat end of the thin metal cup that forms the casing of the detonator. The base charge is located at this end and it will be referred to as the "base end." When prepared for use in the dynamic tests, the wires on the detonator are clipped very close to wire end and do not project more than 1/32 of an inch. The detonator is then inserted along the axis of a projectile filled with C-4 explosive, so that the exposed end of the detonator is flush with or slightly below open end of the projectile casing, and the C-4 explosive packed tightly around it.

The detonator performance tests were conducted using the wire end of the detonator as the exposed end which struck the target. Both the wire end and the base end were oriented as the exposed end of the detonator in subsequent tests. Qualitatively, it appears that the base end is slightly more sensitive to impact than the wire end, however the geometry related to detonation ot the C-4 explosive is somewhat less favorable for the base and exposed configuration.

3. EXPLOSIVE-ROCK INTERACTIONS

A principle concern of this study is the interaction of a detonated explosive and a rock surface. The basic variables include, the amount and configuration of the rock removed as a function of explosive size and number of subsequently detonated charges, the mechanisms associated with rock removal, the interactions associated with successive detonations and the efficacy of this type of hard rock excavation. Both static and dynamic tests were performed and were differentiated by whether the explosive was brought to the rock surface by manual placement or high velocity impact, respectively. The effort was mainly experimental but some theoretical analyses were carried out to provide guidance for the experiments.

The primary interest is with regard to the effects that are obtained with real rock such as granite. However it was obvious early in the program, that the use of real rock in all the experiments would be prohibitively expensive and lead to serious experimental difficulties. Properties vary substantially between individual rocks of the same type, even within specific rock samples. Such variations become a large source of experimental scatter, and thereby increase the number of replicate tests which must be performed to obtain significant results. In addition, in order to eliminate or reduce edge effects, relatively large rock samples must be utilized. Such rocks would have to be individually selected and procured and once obtained, are unwieldy and do not lend themselves to an extensive test program.

In order to avoid some of these problems, concrete was used as a simulated rock test material. Concrete, with pea-gravel aggregate, has relatively consistant properties, it is easy to obtain and cast into the suitable shapes and sizes required for the test program. One difficulty in the use of concrete is the fact that concrete developes it's ultimate strength over a relatively long period of time after casting. Table 1 gives the percent of strength (relative to that at one year) versus time after casting.

TABLE 1 PERCENT OF ONE YEAR STRENGTH OF CONCRETE ATTAINED AS A FUNCTION OF TIME AFTER CASTING

	Time after Casting			
	1 week	1 month	3 months	1 year
% of 1 Year Strength	52%	69%	86%	100%

The concrete used on this program was composed of cement, sand, pea gravel, and water with the following respective average weight proportions: 1: 3.2: 2.5: .44. The pea gravel was that which would pass through a 1/2-inch grating. The average density was 2.4 gms/cm^3 or 150 lbs/ft^3.

The granite used in the experiments was obtained from local quarries. The large pieces were personally picked at the quarry for size, shape, apparant homogeneity, and freedom from visual cracks.

A comparison of granite and concrete properties taken from references 1 and 2 are included in Table 2.

TABLE 2 MECHANICAL PROPERTIES OF GRANITE AND CONCRETE

	Granite	Concrete
Density (gm/cm^3) / (lbs/ft^3)	2.67/167	2.40/150
Compressive Strength (PSI)	19,400	4000-6,500
Tensile Strength (PSI)	~800	350
Modulus of Elasticity (PSI)	7.0×10^6	5.3×10^6
Poisson's Ratio	~.25	.15-.25

Although the granite rocks were large (approximate dimensions 3 ft x 3 ft x 5 ft), there were appreciable edge effects, especially for 1 1/2-inch diameter test charges, and large pieces would fracture and split off from the main piece during a series of explosive shots. This problem in the concrete targets 3-ft-high x 3-ft-dia and 2-ft-high x 2-ft-dia was alleviated somewhat by the confinement provided by the thick, sturdy, cylindrical cardboard concrete form.

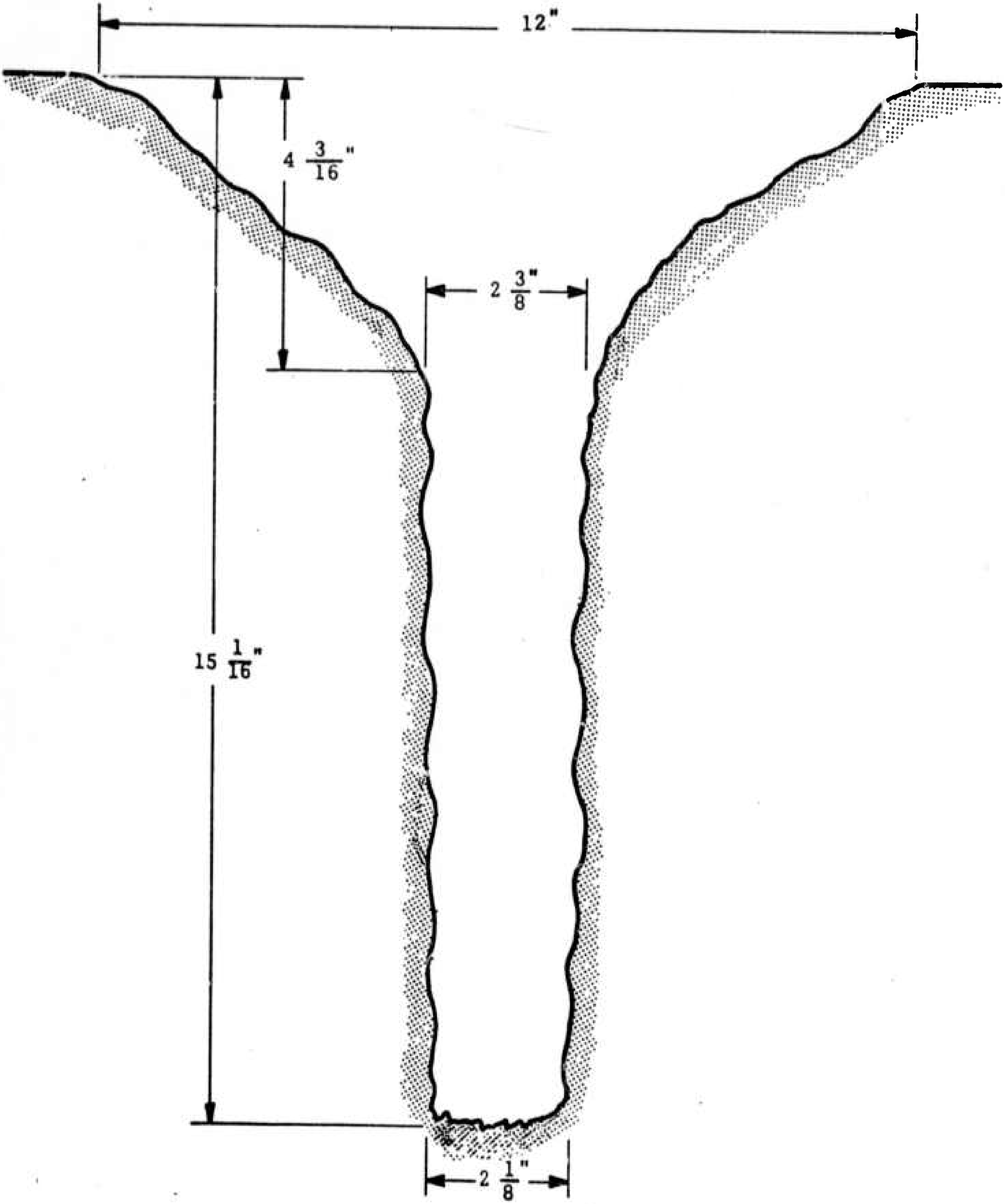

Figure 1 Typical Crater Profile For a Large Number of Successive Explosions of 3/4" dia. x 3/4" high C-4 Charges

Qualitively, similar craters were obtained in granite and concrete with respect to general shape and behavior for multiple shots. The quantitative data is contained in the following sections.

3.1 STATIC EXPERIMENTS

A series of static experiments were performed to investigate the diameter, depth, and volume of rock removed as a function of explosive type, charge size, and the successive effects.

When a long series of static shots are fired into concrete or granite, a hole profile similar to Figure 1 is obtained. The initial 8-10 shots interact strongly with the free rock surface into which the shots are fired and a conical crater results with a diameter many times the diameter of the explosive charge. During this portion of the rock excavation, a relatively large amount of rock volume is removed due to the strong free surface interaction. After this initial configuration, the excavation proceeds as a more or uniform tunnel into the rock, with much less interaction with the free surface. The depth of rock removed per shot is somewhat greater in the initial shots, near the free surface, and settles down to an approximately constant value in the later tunneling phase.

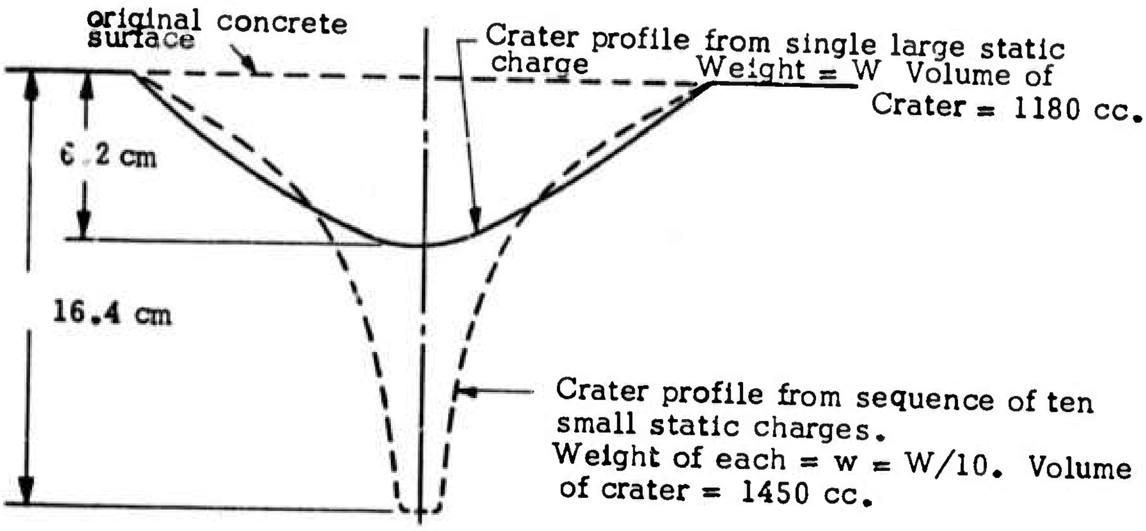

Figure 2 Comparison of the Effects of Multiple vs. Single Charges of the Same Total Weight

A comparison between the effects of a single charge and a series of 10 multiple charges totaling to the same weight as the large charge, was made and the result appears in Figure 2. As can be seen, greater volume of rock removal and much greater depth is obtained with the multiple charges. The charges used in the multiple series were as shown in Figure 3, except no aluminum casing surrounded the charge. The single large charge was similar in shape to the small charges except that the height and diameter were larger by the factor, the cube root of ten.

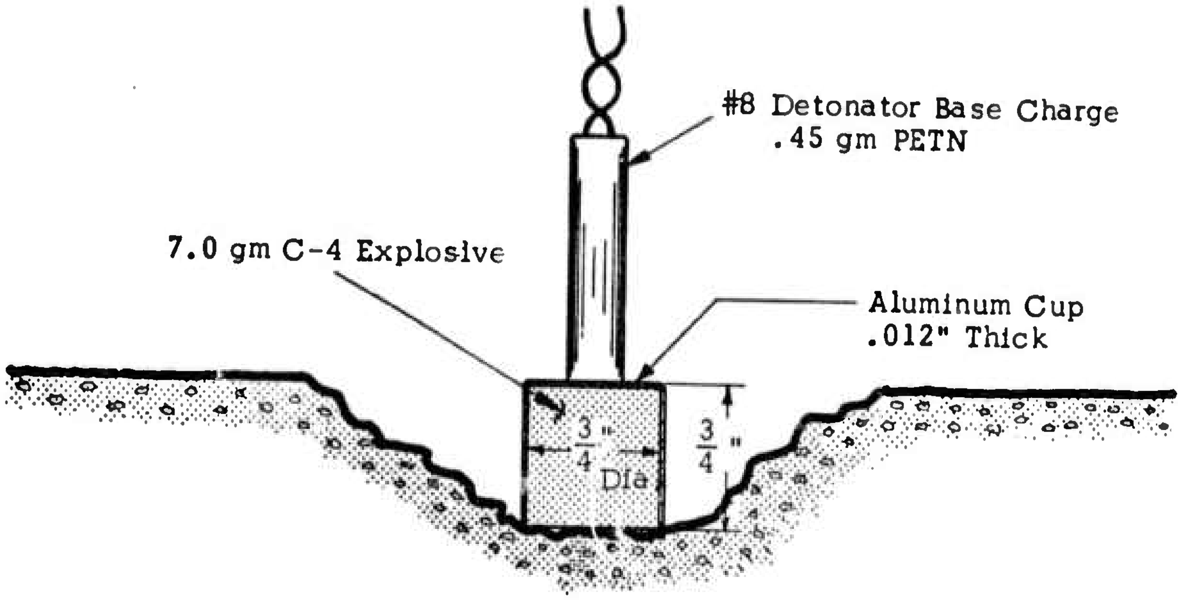

Figure 3 Static Test Configuration

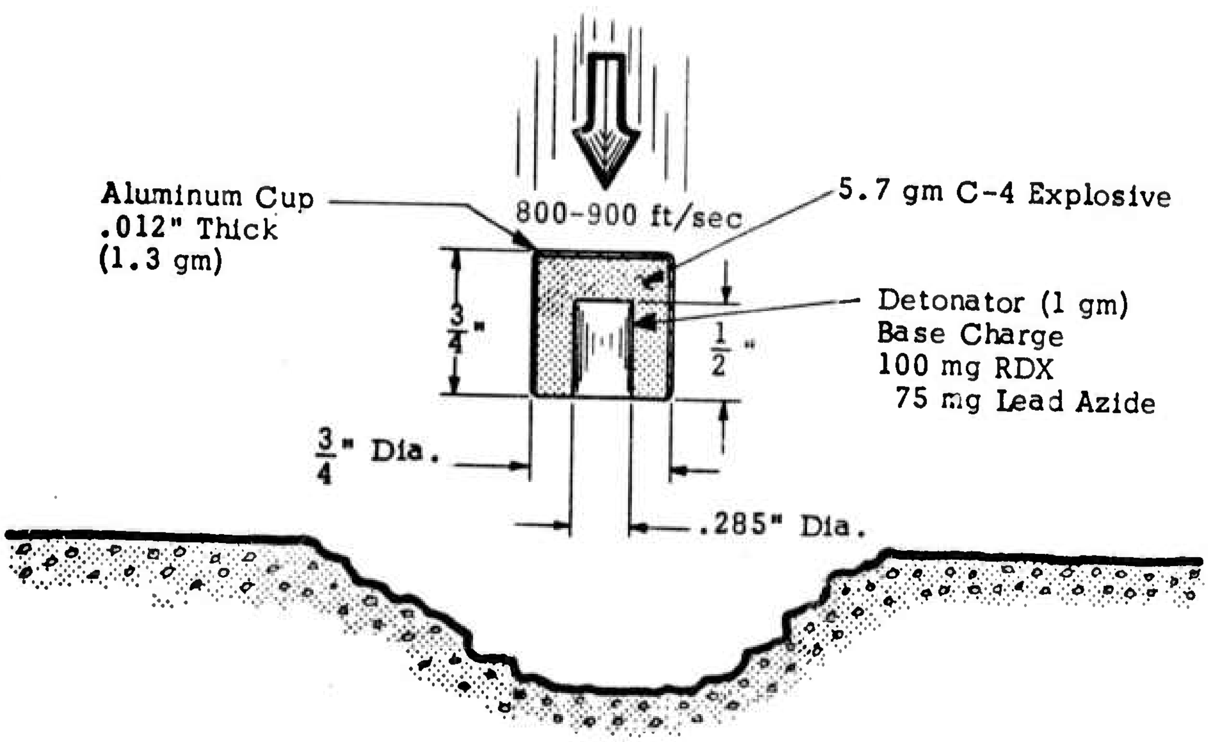

Figure 4 Dynamic Test Configuration

The small charge shown in Figure 3 was the standard small charge used in most of the static tests.

Investigation was made of the precracking effects between successive explosive projectiles. When a series of small explosive projectiles successively detonate on a rock target surface, each charge, after the first, encounters rock that is not wholly intact. That is, besides removing a certain volume of rock, each charge also leaves around the cavity a volume of rock that contains numerous cracks and fractures. This precracking should have an effect on the rock removal efficiency of the following explosive projectile.

Tests were conducted to investigate the effects of pre-cracking on the excavation efficiency of a small explosive charge. It is desirable that the pre-cracking used in such tests simulate the pre-cracking obtained by an explosive charge. It is also desirable that in generating the simulated precracking, one should avoid doing excessive damage such as breaking free large masses of the sample, in order to isolate pre-cracking with respect to a sample of uncracked material. Pre-cracking was induced into the flat surfaces of granite blocks by placing a 6" x 6" square of .25-inch-thick steel plate on the granite surface and detonating a 3/4" x 3/4" cylindrical explosive charge on the center of the plate. Although virtually no granite material was removed, there was extensive surface cracking of the granite. Use of a fluorescent dye penetrant revealed numerous radial and circumferential cracks in the granite around the area directly below the base of the explosive charge. However when subsequently an explosive charge was detonated directly on the granite surface centered on the pre-cracking region, the crater depth and volume did not differ significantly from what was obtained from a similar charge detonated on an uncracked portion of the granite surface. Analogous results were obtained on concrete.

Fluorescent dye penetrant was also applied to a granite sample subjected to the standard static charge and then sectioned through the crater subsequently formed by the explosion. Although somewhat greater cracking was obtained under the crater for this case, it did not appear to differ significantly from the simulated pre-cracking case. In both cases separate and distinct radial and circumferential cracking appear around a heavily fractured area below the surface. This heavily fractured area is about 1-2 charge diameters in height and width. Distinct cracks extend over five or more charge diameters into the granite. The implications of these results are discussed further in the section on multiple projectile interactions.

3.2 DYNAMIC EXPERIMENTS

The projectiles fired from the launchers, in the dynamic experiments, were all similar to that shown in Figure 4, except for some tests in which the detonator was positioned transverse to the axis of the projectile. Only the concrete targets were used for the dynamic experiments.

The dynamic tests investigated the depth and diameter resulting from a series of projectiles fired from the launchers, the effects of varying the orientation of the detonator, and the damage from a high velocity projectile with a detonator but without the high explosive. Several projectiles containing a detonator but with the high explosive replaced by clay were fired into a steel plate at 900 ft/sec. The detonator was initiated by the impact but in each case, inspection of the

.250-inch-thick steel plate after the shot showed virtually no damage to the plate other than some discoloration of the surface at the impact point. When the same projectile configuration, but with high explosive packed around the detonator, was fired at and initiated by impact with the steel plate, the plate was perforated and severely deformed around the impact point. This represents significant proof that detonation of the high explosive represents virtually all the source of damage from the projectiles. The orientation tests showed that axial orientation of the detonator provided the best performance.

3.3 ANALYSIS OF DATA FROM THE STATIC AND DYNAMIC TESTS

Tables 3, 4, 5, and 6 give the results obtained from the static and dynamic tests relative to the excavation of rock by small explosive charges. Figures 5 and 6 show depth and volume for cavities formed by successive detonation of the 3/4-inch-high by 3/4-inch-diameter C-4 explosive charges. Most of the curves are taken only up to the tenth charge. After the tenth charge the depth per charge remains fairly constant. While the depth per charge is fairly consistent, the volume per charge varies considerably, especially for the granite. During the initial cratering phase, while there is a strong interaction between the shock wave generated by the explosion and the surface, large pieces of rock will break off or split away from the main piece of rock. This gives high volumetric efficiency for the initial charges with the largest efficiencies indicated for charges that explodes at some position below the original surface. However, after some point, the interaction with the surface rapidly decreases and the tunneling phase of the excavation is reached and the volume/charge removed quickly becomes stabilized at some lower value equal to the steady state depth per charge times the area of the hole. Generally for large scale removal of rock it is advantageous to have strong interaction with the shock wave and the free surface, as in bench type blasting. Since there is likely to be little interaction with the free surface during most of a hole explosively drilled into a flat rock face, the amount of rock removed by explosive drilling appears small when compared to the amount removed in conventional bench blasting, but due to the special nature of drilling, as compared to bench blasting with already completed drill holes and undercuts, such a result is to be expected. However, it should be emphasized that, since drilling is the most time consuming process in large scale rock excavation, advances in drilling speed contribute significantly to the speed of rock excavation as a whole.

In Table 3, comparing the effectiveness of various explosives, in the 3/4-inch-size, it can be seen that an Octol cylinder with 1.19 times greater mass, due to its higher density, gives 1.51 times greater depth per shot, compared to C-4. Composition B explosive gives only 1.02 times greater mass of explosive than a C-4 cylinder of the same size. The reason for the anamolous result for Composition B is not certain since the projectile size should be above the critical size (< 1/4 inch) for full detonation of Composition B. A few low order detonations with the Composition B charges were obtained and this tends to indicate that these 3/4-inch cylinders of Composition B are near critical size. It seems reasonable that much better performance would be expected for larger Composition B cylinders. Table 4 shows that there was very little significant difference between the static and dynamic depth per shot for 3/4-inch C-4 cylinders.

The comparison in Table 5 indicates that on the basis of weight of material removed vs. weight of explosive, the smaller explosive charges are slightly, but not significantly, more efficient. This result agrees with the test in which the effectiveness of 10-3/4-inch charges was compared to a single charge of the same mass.

TABLE 3. EFFECTIVENESS OF VARIOUS EXPLOSIVES (STATIC)

Charge Size (inches)	Explosive	Density (gms/cc)	Avg. Depth/Shot (inches)	Avg. Depth/Shot (cm)
3/4 x 3/4 Dia	Comp. B	1.51	.560	1.422
"	C-4	1.29	.550	1.397
"	Octol	1.54	.830	2.108

TABLE 4. STATIC VS DYNAMIC PENETRATION

Charge Size (inches)	Explosive	Type	Avg. Depth/Shot (inches)	Avg. Depth/Shot (cm)
3/4 x 3/4 Dia	C-4	Static	.550	1.397
"	"	Dynamic	.536	1.361

TABLE 5. CONCRETE REMOVAL VS. SIZE (STATIC)

Charge Size (inches)	Explosive	WT. of Concrete Removed / Explosive Weight	Depth/Shot (inches)
3/4 x 3/4 Dia	C-4	14.4	.550
1 x 1 Dia	C-4	13.0	.776

TABLE 6. DRILLING SPEED (DYNAMIC) -3/4" x 3/4" DIA C-4 CHARGES @ 50/SEC

Target Material	Inches/Projectile	Drilling Speed (ft/ min)
Concrete	.536	134
Granite	.407*	102

*Estimated by Granite (Static) $\times \frac{\text{Concrete (Dynamic)}}{\text{Concrete (Static)}}$

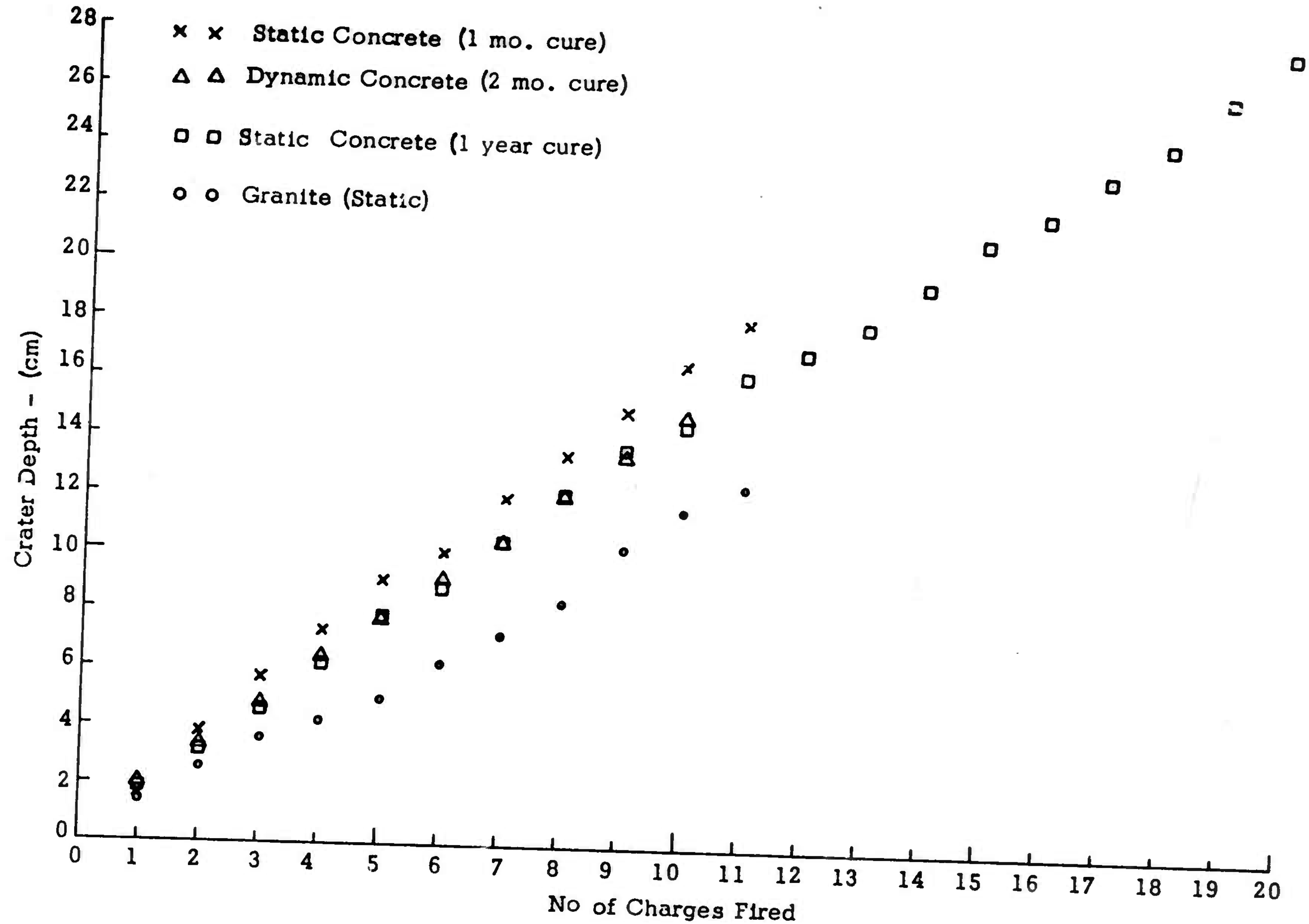

Figure 5 Crater Depth vs Number of Successive Charges Fired

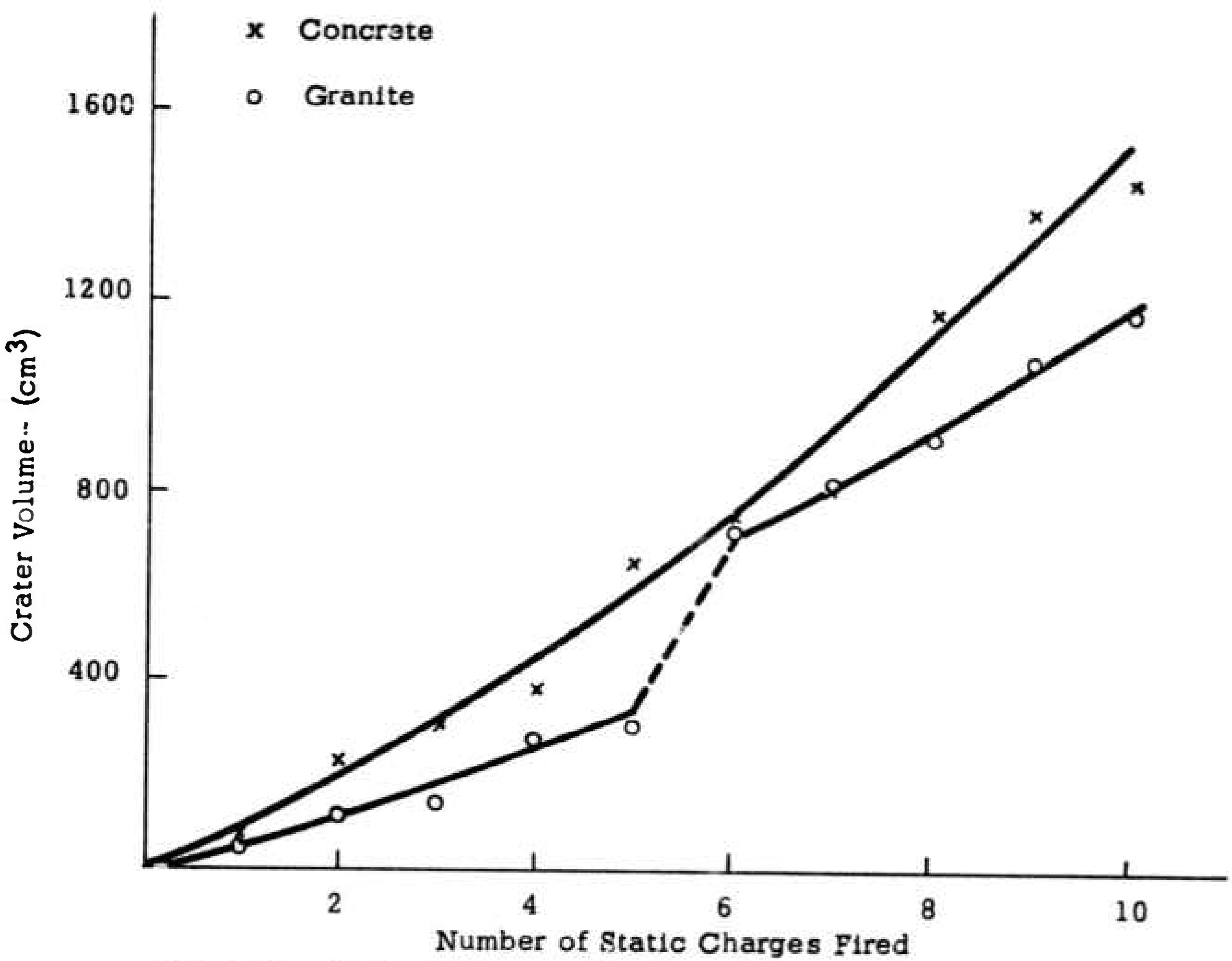

Figure 6 Crater Volume vs Number of Successive Charges Fired

The estimated possible drilling speed through concrete and granite for 3/4-inch C-4 charges is presented in Table 6. This estimate is calculated from the measured average depth per shot for both materials and actual firing rates obtained for trains of projectiles in the multiple launcher. These drilling speeds, for a hole over 2-inches in diameter, are at least an order of magnitude faster than what can be achieved by the fastest conventional methods and represents a considerable advance in the state of the art.

3.4 DEPTH PER SHOT SCALING

Crater formation by explosive charges can be considered as a function of the shape and size of the explosive charge, the characteristics of the explosion and the material characteristics of the target i.e.,

Crater Depth $\propto$ (Size Factor) x (Explosive Factor) x (Target Material Factor)

It has been found that in many instances explosive effects tend to scale as the cube root of the explosive weight. Figure 7 is a graph of crater depth/shot vs the cube root of weight for several C-4 explosive charges. The graph shows that the charge configuration in which the diameter is larger than the height is somewhat more efficient in crater formation than the case in which the diameter is equal to the height. This result agrees with the hypothesis in Reference 3 where crater depth is associated with the time duration of the shock wave generated by the explosion, which is approximately a function of the charge radius or height, which ever is less. Thus explosive configurations would be expected to be less efficient where either the radius or height appreciably exceeded the other dimension. For ballistic reasons, the standard projectile configuration used in this program was a cylinder with height and diameter equal and the crater depth relationship will be developed with respect to this configuration. In bench blasting, where a charge is detonated in a hole parallel to a large free surface, explosives with relatively moderate detonation pressure and brisance have proven effective. However, crater formation is more likely to be enhanced by the brisance, than by the heaving power, of an explosive. In this case it would be expected that the detonation pressure of the explosive would be a good indicator of its effectiveness in cratering. The detonation pressure for the C-4 and the Octol explosive used in the 3/4" x 3/4" charges was calculated and plotted as a function of crater depth/shot in Figure 8. The detonation pressures (P) were calculated from the formula

$$P = \rho_0 D^2/\gamma + 1$$

where ρ_0 is the charge density, D is the detonation velocity and γ is the adiabatic constant considered to have a value of 3.0 for both explosives. The detonation pressures are displayed in Table 7.

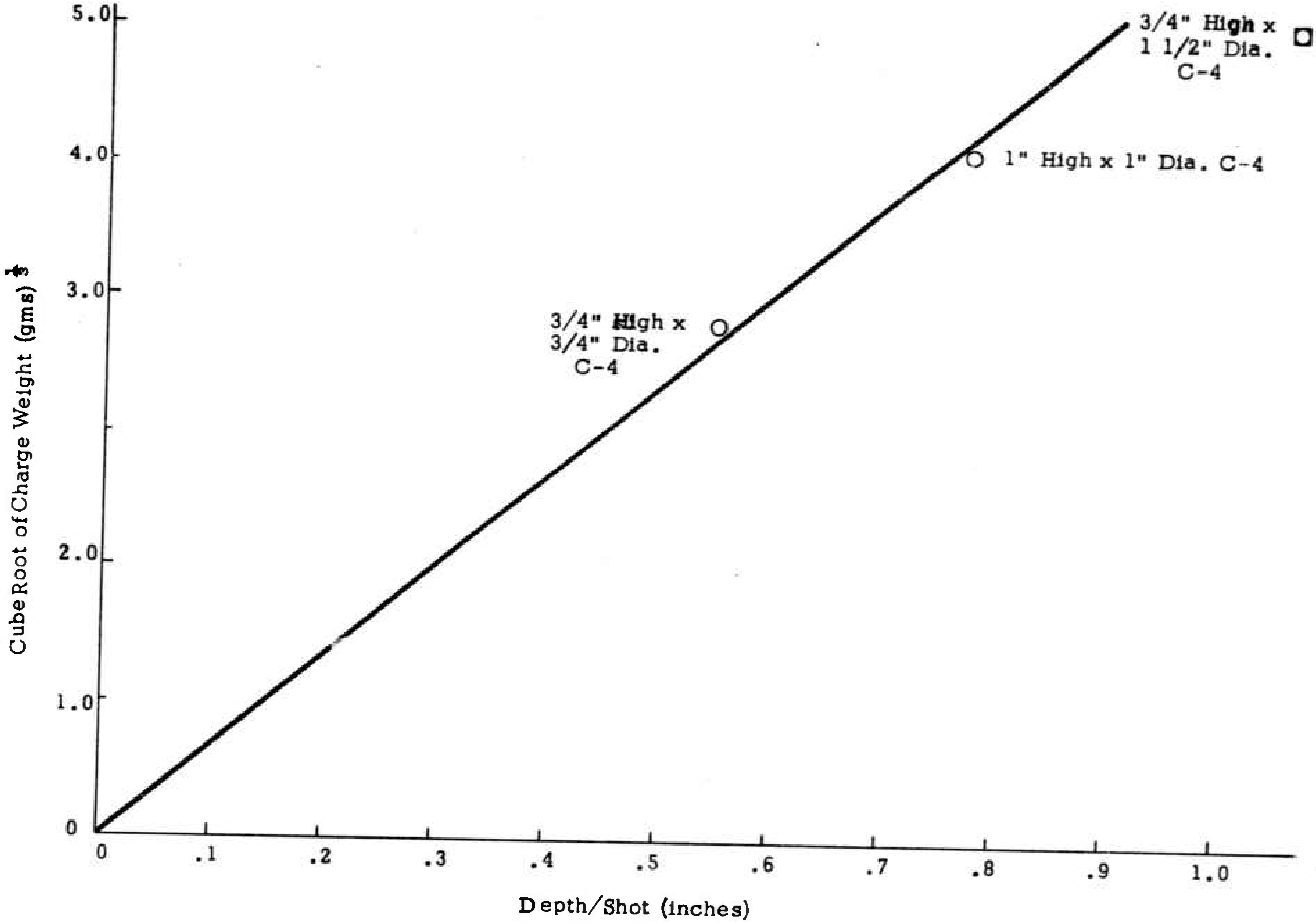

Figure 7. Cube Root of Charge Weight vs Depth/Shot

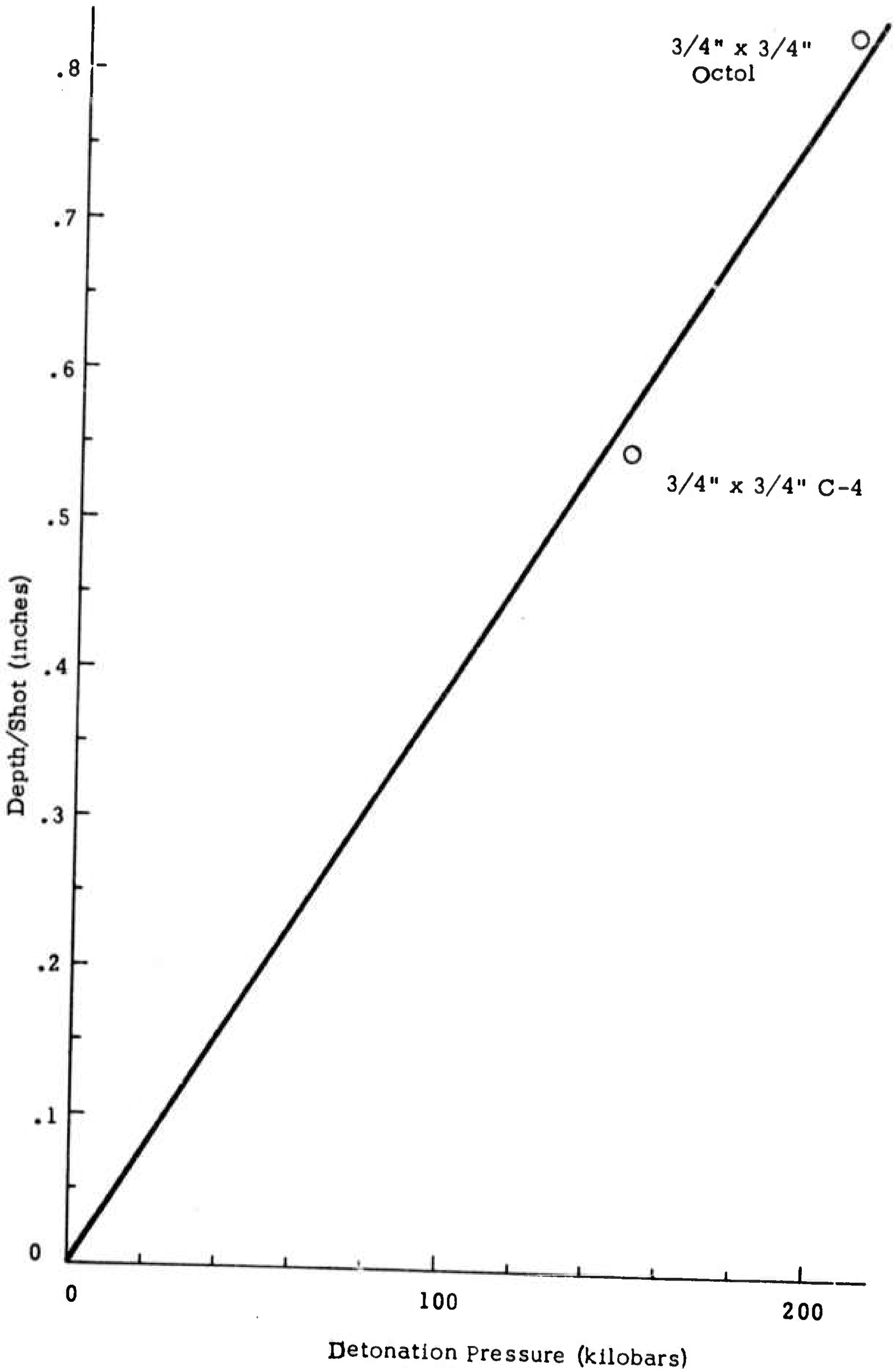

Figure 8. Depth/Shot vs Detonation Pressure

TABLE 7 CALCULATED DETONATION PARAMETERS FOR C-4 AND OCTOL

Explosive	Charge Density (gm/cc)	Calculated Detonation Velocity (m/sec)	Calculated Detonation Pressure (kilobars)
C-4	1.29	6790	150
Octol	1.54	7420	210

The effect of the target material properties on crater depth formation is an extremely complicated subject for which adequate closed form relationships are not yet available. Just on the most general basis it can probably be assumed that the crater formation is in a large part due to shear failure. For many materials the shear strength is the same fraction of the shear modulus, Ref. 4 and 5. Assuming this is true and assuming also that the depth/shot is inversely proportional to the shear strength, then the depth/shot is inversely proportional to the shear modulus. The reciprocal shear modulus is plotted vs. depth/shot for granite and concrete in Figure 9. Also plotted is a point for a crater formed in a steel target by a 3/4-inch-diameter x 2-inch-high C-3 charge reported in Reference 3. Even though the charge is 2 inches high rather than 3/4" high it is believed that this data should be comparable to the other data since it is the smallest dimension of the charge geometry that has the major influence on the pressure duration and hence the blast effects. The data for the graph is given in Table 8.

TABLE 8 CALCULATED SHEAR MODULUS VS DEPTH/SHOT FOR 3 MATERIALS

Material	Mod. of Elasticity $x10^{-6}$ (PSI)	Poissons Ratio	Calc. Shear Mod. $x10^{-6}$ (PSI)	Calc. Recip. Shear Mod. $x10^{6}$/(PSI)	Depth/Shot (inches)
Concrete	5.3	~.25	2.1	.476	.550
Granite	7.0	~.25	2.8	.357	.418
Steel	30.0	.30	11.5	.087	.098

The excellent straight line fit observed in Figure 9 is interesting, although the theoretical basis for the relationship is admittedly not fully rigorous. However, using this fit combined with the fits for the data to the weight and detonation pressure, the equation for the predicted depth/shot in terms of the target and explosive properties becomes,

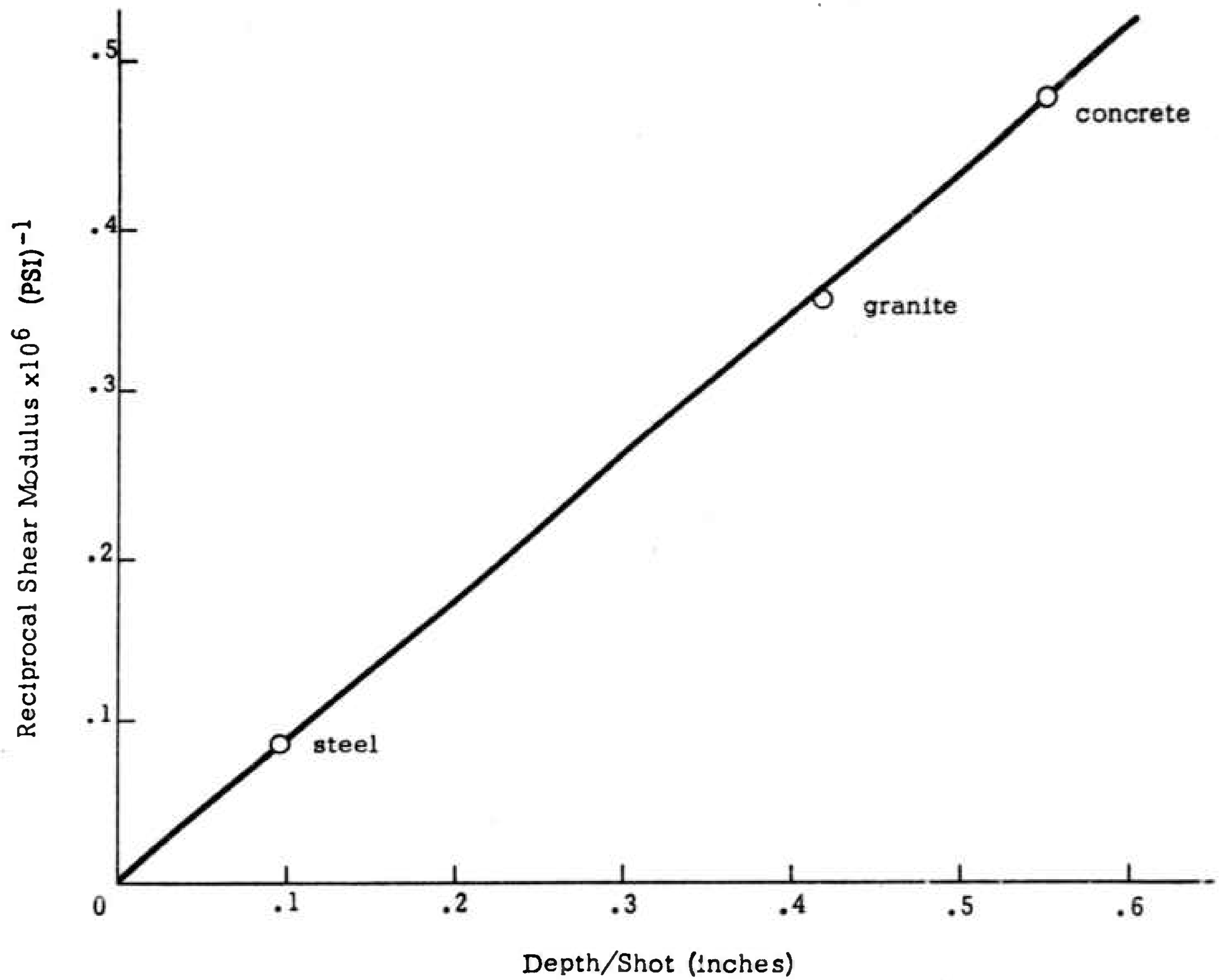

Figure 9. Reciprocal Shear Modulus vs Depth/Shot for Various Materials

$$\text{depth/shot} \approx 4030 \; \frac{(W)^{1/3} P}{G}$$

where W is the charge weight in grams

P is charge detonation pressure in kilobars

G is target shear modulus in PSI

Table 9 gives the comparison between predicted and actual crater depth/shot for tests where the charge was a cylinder of equal diameter and height. As can be seen the predicted and experimental results are in very good agreement.

4. MULTIPLE CHARGE LAUNCHER

A prototype multiple charge launcher was needed in the program both to accelerate a closely-spaced sequence of explosive charges to velocities sufficient to produce initiation and to also explore the feasibility of accelerating a very extended series of charges as might be used in a real hard rock excavation process. A launcher was utilized in the early dynamic tests that could accelerate small explosive charges to a velocity sufficient to actuate a forward facing detonator imbedded in the charge, but this launcher had only single shot capability. The prototype multiple launcher that was developed was designed to meet both of the above requirements i.e., to be able to fire short sequences of charges with a very small time interval between charges and also to be capable of firing very long sequences of charges.

4.1 MULTIPLE LAUNCHER DESIGN

Several features were determined to be important in the design of a prototype launcher. These were:

(a) The design should be as mechanically simple as possible.

(b) The explosive projectiles should not be exposed to a hot driving fluid or pass through a barrel that has been heated to high temperature by firings of previous projectiles.

(c) The spacing, loading, and firing of the explosive projectiles should be done in such a manner that there is little possibility for crushing or jamming the projectiles. Complicated mechanical projectile handling devices should be avoided.

(d) A means of counting the projectiles, measuring their separation, and their velocity would be needed to effectively use the launcher.

Implementation of these criteria resulted in:

(a) Utilization of pneumatic operation to minimize difficulties from mechanical devices. Pressurized gas was used as the driving fluid. Thus the explosive projectile is not exposed to

TABLE 9 PREDICTED VS ACTUAL DEPTH/SHOT FOR EQUAL DIAMETER-HEIGHT CYLINDRICAL STATIC CHARGES

Explosive	Weight (gms)	$\sqrt[3]{W}$	Detonation Pressure (Kilobars)	Target Material	Shear Modulus x 10-6 (PSI)	Predicted Depth/Shot (inches)	Experimental Depth/Shot (inches)	Difference
C-4	7.0	1.913	150	Concrete	2.1	.551	.550	.2%
C-4	7.0	1.913	150	Granite	2.8	.413	.418	1.2%
C-4	16.0	2.551	150	Concrete	2.1	.734	.776	5.4%
OCTOL	8.3	2.025	210	Concrete	2.1	.816	.830	1.7%

high gas temperatures and the expansion of the gas in the barrel for successive projectiles tends to cool the barrel.

(b) An open tube, canted port design was employed so that the projectiles, during loading and firing, would be serially contained in a tube of approximately constant diameter and never pass sections which are periodically closed by mechanical means, such as a breech lock.

(c) An electronic system utilizing a pair of photo cell stations at the muzzle of the launcher, so that the passage of any number of projectiles could be detected without impeding the projectiles in any way.

A schematic of the launcher and basic firing operation is shown in Figure 10 a and b. The design drawing of the main launcher is displayed in Figure 11. The design drawing of the sequencer is displayed in Figure 12. A schematic of the launcher auxiliary equipment appears in Figure 13. Engineering drawings are presented in the Appendix.

Referring to the figures, the operation of the launcher is as follows: A train of separated 3/4-inch-diameter by 3/4-inch-long projectiles are supplied to the main launcher by a supply tube, of any convenient length and capacity, through the sequencer. At the present time, a gas supply is held in a pressure chamber, but for long trains of projectiles a continuous source of high pressure gas would be needed. At the start of the operating sequence, the pressure chamber is closed off from the barrel by a movable ring valve. The ring valve is held in place by high pressure applied on the side away from the annular pressure chamber. When the firing button is pushed, the gas is evacuated from this side of the ring valve by the opening of a solenoid valve. The pressure in the pressure chamber, then pushes the ring valve forward, uncovering the four canted gas jet ports. The gas rushes through the ports and up the barrel. As a projectile is pushed into the port area, the gas flow catches it and accelerates it up the barrel.

The projectiles are separately pushed into the port area by the sequencer, Figure 12. The sequencer is composed of a back section that connects to the projectile supply tube, a center section that is set off by two O-rings and a forward section that connects to the accelerator tube of the main launcher. The projectile supply tube is assumed to be filled with a train of projectiles in contact with each other. The following pressures (P) and maximum available flow rates (Q) are applicable.

P_1 = pressure on train of projectiles and in back section

Q_1 = maximum flow rate of gas into back section of sequencer

P_2 = pressure input to center section of sequencer

Q_2 = maximum flow rate input to center section of sequencer

P_3 = back pressure behind ports with no projectile in the barrel

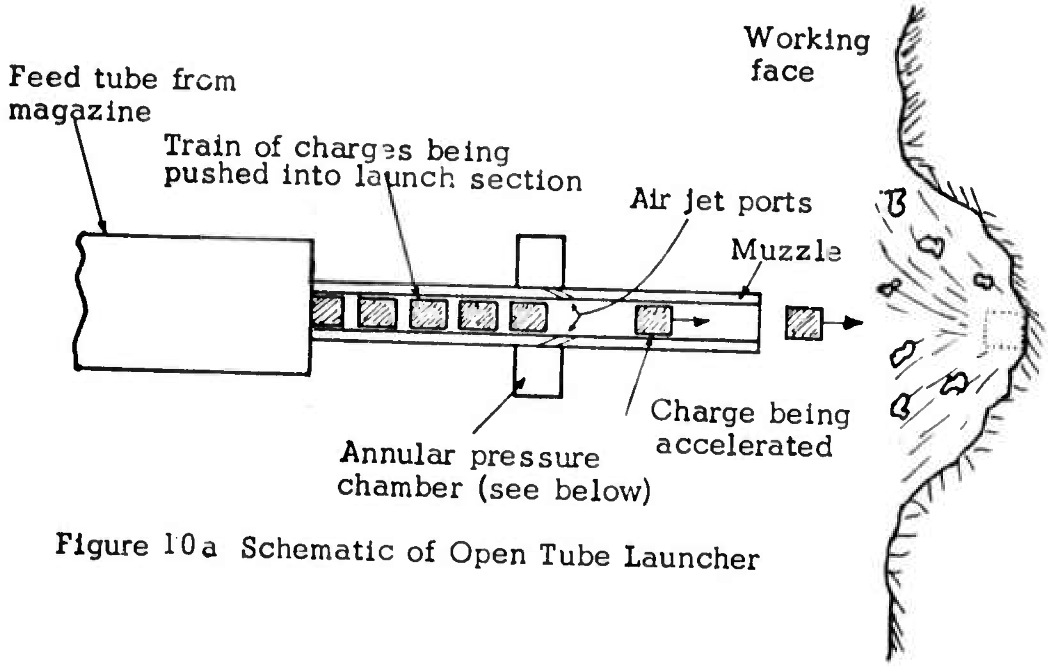

Figure 10a Schematic of Open Tube Launcher

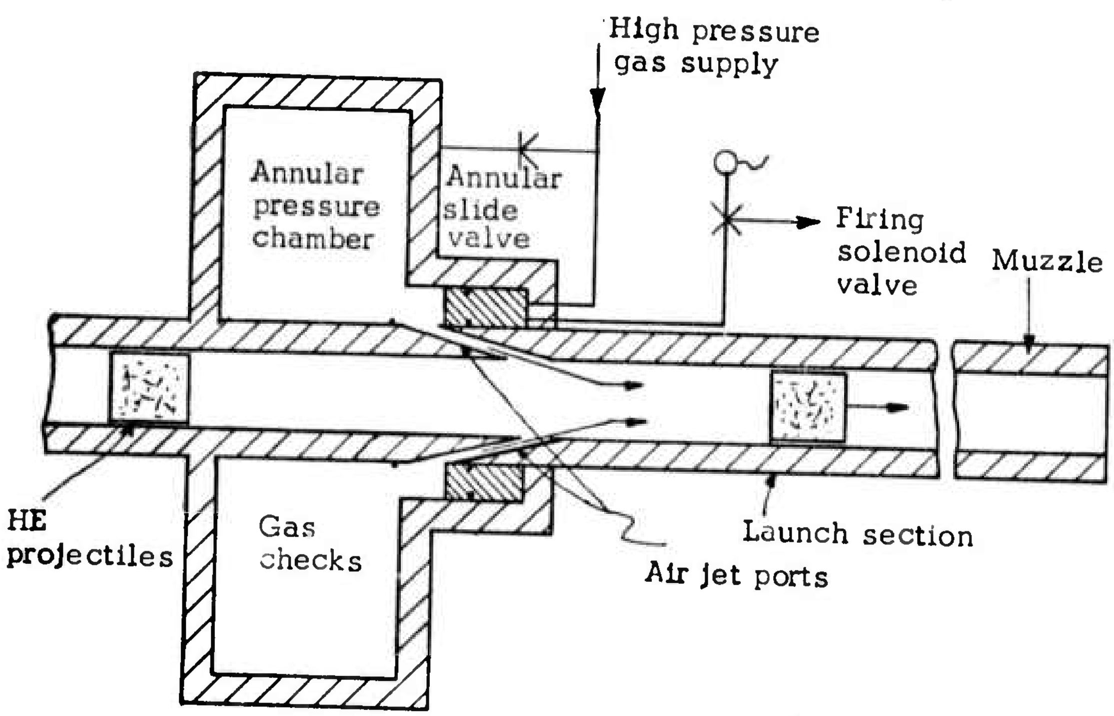

Figure 10b Schematic of Air Jet Port Station

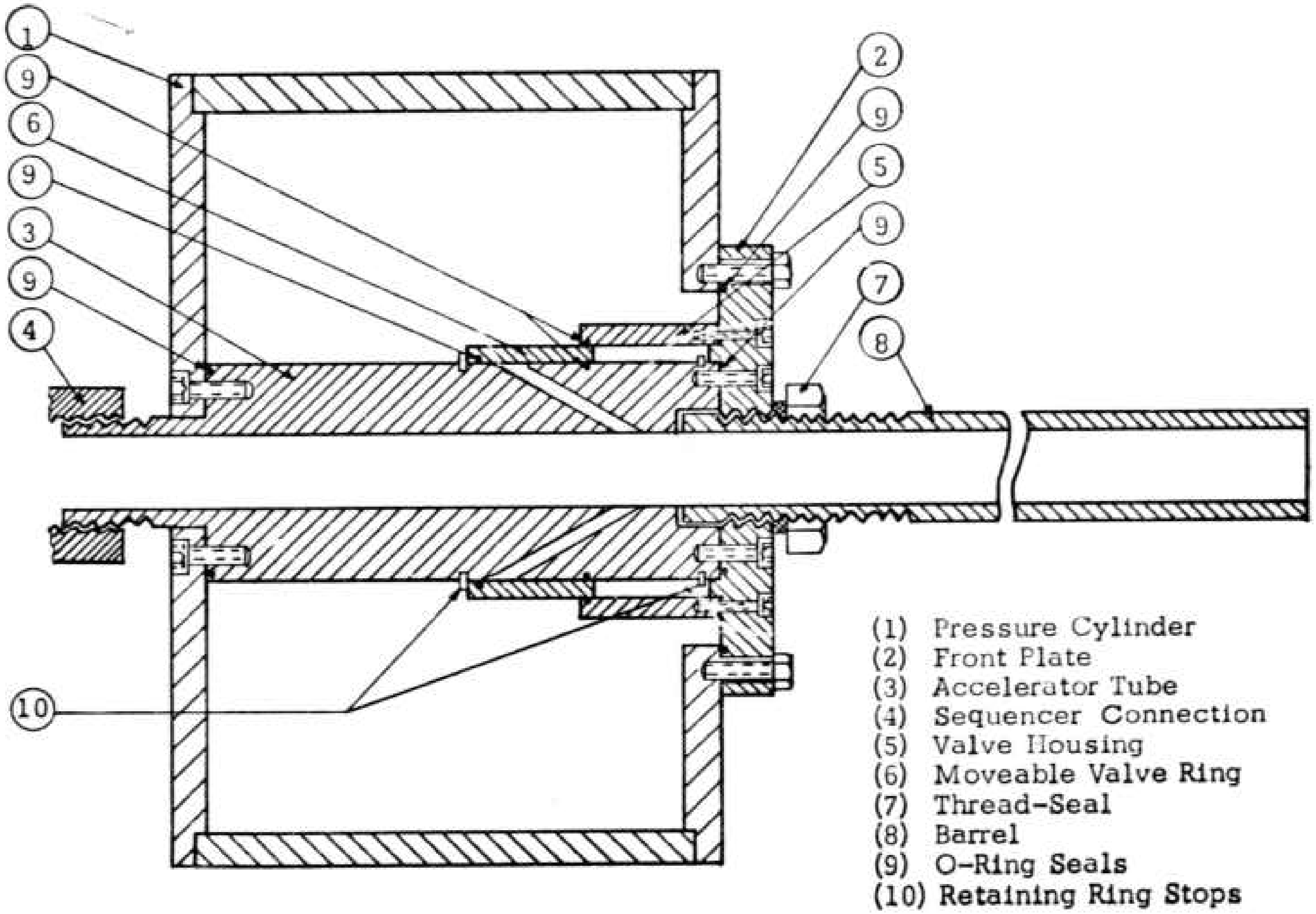

Figure 11 Main Launcher

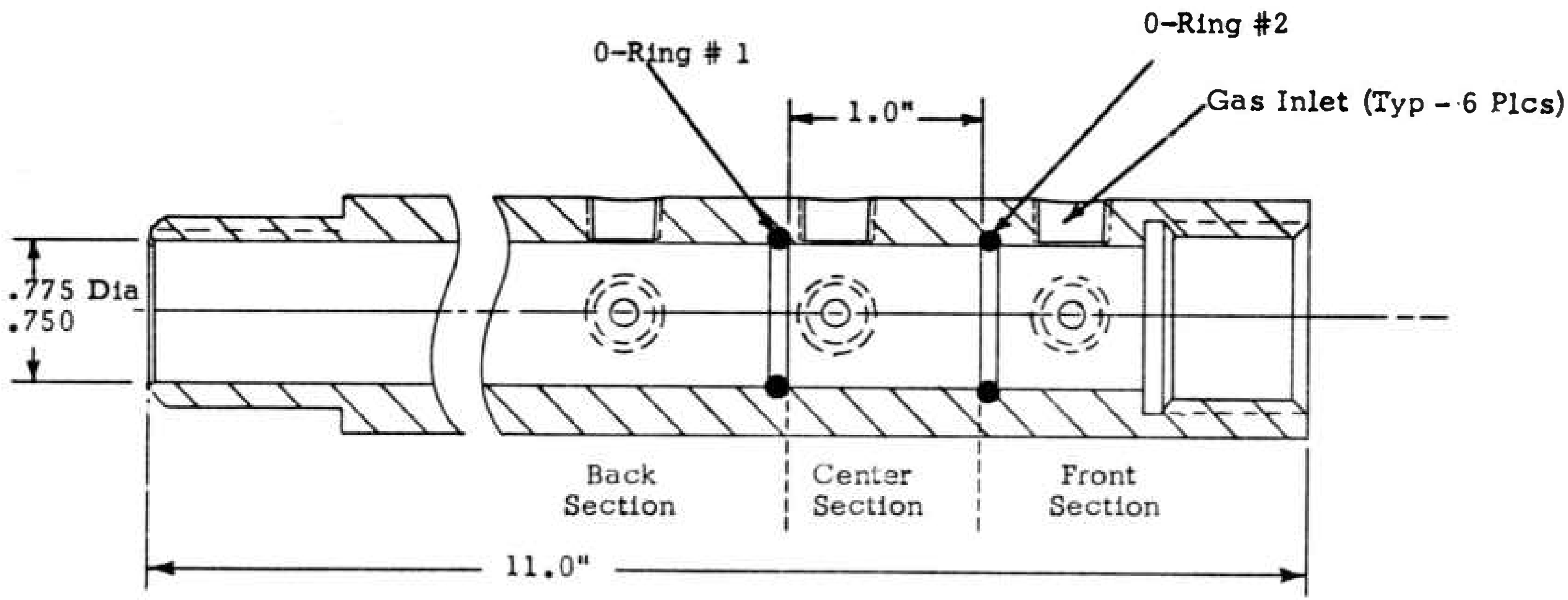

Figure 12 Sequencer

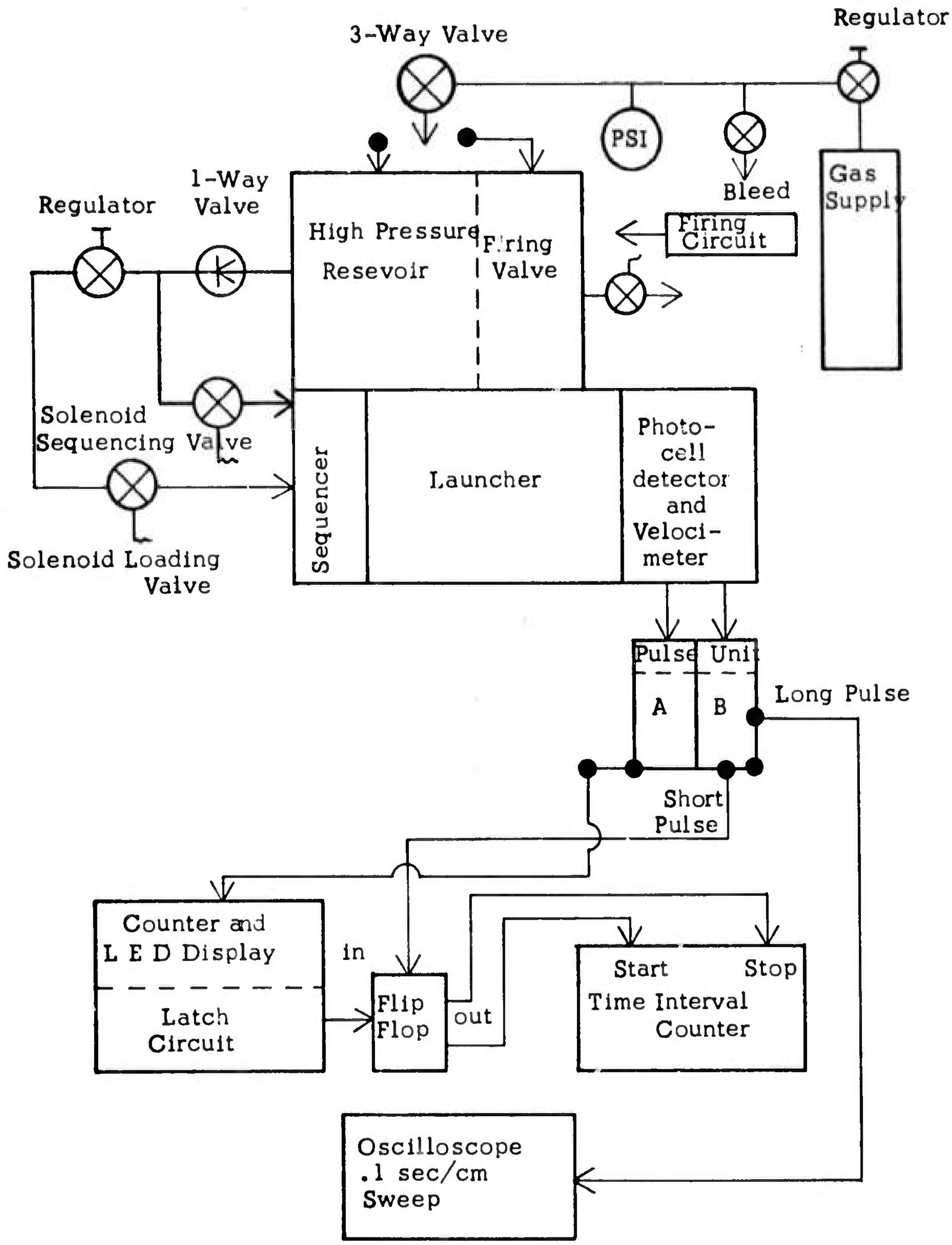

Figure 13 Schematic of Launcher and Auxiliary Equipment

P_4 =back pressure behind ports with a projectile in the barrel

ΔP =pressure differential required to push projectile past O-ring

Q = maximum flow rate through ports.

The general relationships between the pressures and flow rates for operation of the sequencer with the main launcher is:

$$P_2 > P_4 + \Delta P > P_1 > P_3 + \Delta P \qquad \text{and,}$$

$$Q > Q_1 > Q_2$$

At the beginning of the sequencing action, the train of projectiles is pushed up to the first O-ring (O-ring #1) between the back and center sections of the sequencer. The gas flow is then started through the canted ports, the back and the center section of the sequencer. With an open barrel, the restricted flow Q_2 adds very little to the pressure P_3 in front of the first projectile. However since $P_1 > P_3 + \Delta P$ and the projectile seals against O-ring #1, the projectile is pushed past O-ring #1 and seals against the following O-ring (O-ring #2). When the projectile seals against O-ring #2, the center section is isolated from the barrel and the restricted flow Q_2 can quickly build up the pressure in the small portion of the center section not filled with the projectile. This pressure holds back the train of projectiles and forces the projectile past O-ring #2 into the port area. As the gases rushing through the port catch the projectile and accelerate it down the barrel, the back pressure in the barrel rises to P_4. With the projectile in the barrel, the restricted flow Q_2 cannot maintain the pressure P_2 and the pressure in front of the next projectile quickly falls to P_4. This pressure is sufficient to hold back the train of projectiles, since $P_4 + \Delta P > P_1$, but after the projectile exits from the muzzle of the launcher, the pressure soon drops to P_3. Since $P_1 > P_3 + \Delta P$, the loading sequence begins again and repeats for each successive projectile in the train until the gas supply is cut off.

The time between projectiles would be equal to the sum of the times to load, to accelerate to the muzzle and for the rarefaction wave to travel from the muzzle back to the next projectile. Based on the gun dimensions and a muzzle velocity of 800 ft/sec, the second two times add up to approximately 17 milliseconds, and the time between projectiles is equal to 17 millseconds plus the loading time. Thus, this launcher, for an extremely fast loading time, would have a maximum fire rate of about 59 projectiles per second or approximately 3540 projectiles a minute.

Information on the sequencing and velocity of the projectiles is obtained with the electronic equipment shown in Figure 13. A six-inch long phenolic tube, slipped about two inches over the launcher muzzle holds a pair of photo cells with opposed prefocused light bulbs. The photo cells and light bulb sets are three inches apart from center to center along a direction parallel to the axis of the barrel and the light beams pass through the axis of the barrel so that a projectile leaving the launcher muzzle will break the beam between a light bulb and the respective photo cell. The associated electronic circuit

connected to the photo cell generates both long (~ 10 millisecond) and short (~ 10 microsecond) pulses for each projectile passage. The long pulses, can be displayed on an oscilloscope to show the spacing of the successive projectiles. The short pulses are sent to a special electronic circuit that counts the number of projectiles exiting from the muzzle of the launcher and, for any chosen projectile in the sequence, will direct the pulses, generated as the projectile passes the two photo cell stations, A and B, to a time interval counter to provide a measurement of its velocity.

Figures 14 and 15 show the multiple launcher as it is installed in the test facility and an overall plan view of the test facility. The launcher is surrounded by a heavy concrete tube and sand embankments to prevent any danger to operating personnel from the blast of the explosive projectiles or the event of an accidental explosion during firing of the launcher.

4.2 MULTIPLE LAUNCHER PERFORMANCE

Following installation of the launcher and connection of the associated pneumatic and electrical supply and firing circuits, tests were performed to provide a preliminary evaluation of its operating characteristics. The launcher functioned well mechanically, and a series of single projectiles were fired to check the obtainable launch velocities. It was found that when fired at rated pressure, the launcher gave projectile velocities close to the design velocity. Even when fired at less than one third of rated pressure, the projectile velocity was still higher than the minimum velocity necessary for the initiation of the detonators in the explosive charge.

After installation and preliminary testing of the sequencer, a series of multiple projectile launches was completed using both inert and explosive projectiles. Trains of up to ten inert projectiles were successfully fired at rates of approximately 50 projectiles per second. Three mutually checking methods of determining whether the projectiles were sequenced properly and launched separately were utilized. The first was the signal generated by a photocell, at the muzzle of the gun, as projectiles passed by. A pulse is emitted by the photocell circuit when the projectile arrives at the photocell station and blocks the light beam to the photocell. A second pulse cannot be emitted by the photocell circuit unless there is another sequence of (a), light received by the photocell for a short time followed by (b), blockage of the light. Thus if the projectiles are accelerated in the launcher all together in a single contiguous bunch, the photocell circuit would emit only one pulse. The signals generated by the photocell circuit during the multiple launches were multiple pulses corresponding to the number of projectiles. Secondly, the velocity of any of the projectiles in the train of explosives can be monitored by the auxiliary instrumentation. Thus the electronic circuit counts the number of projectiles exiting the muzzle of the launcher and, for any pre-chosen projectile in the sequence will direct the pulses, generated as the projectile passes two phtotcell stations 3-inches apart, to a time internal counter, to provide a measurement of its velocity. The velocity of a single projectile launched down the tube should be approximately 800 ft/sec if sequenced correctly. Since the theoretical launch velocity is inversely proportional to the square root of the projectile weight, even a grouping of two

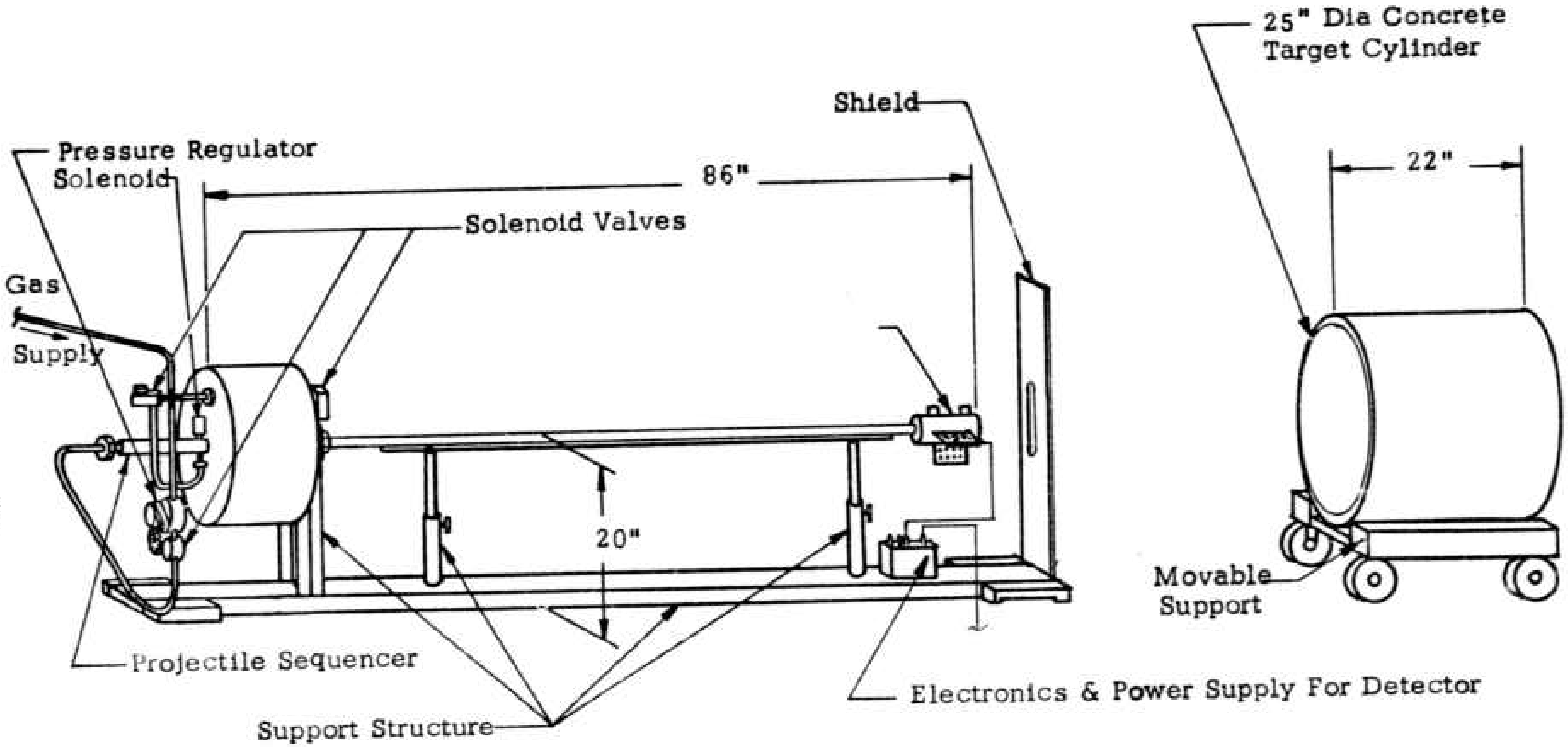

Figure 14 Multiple Launcher Installation

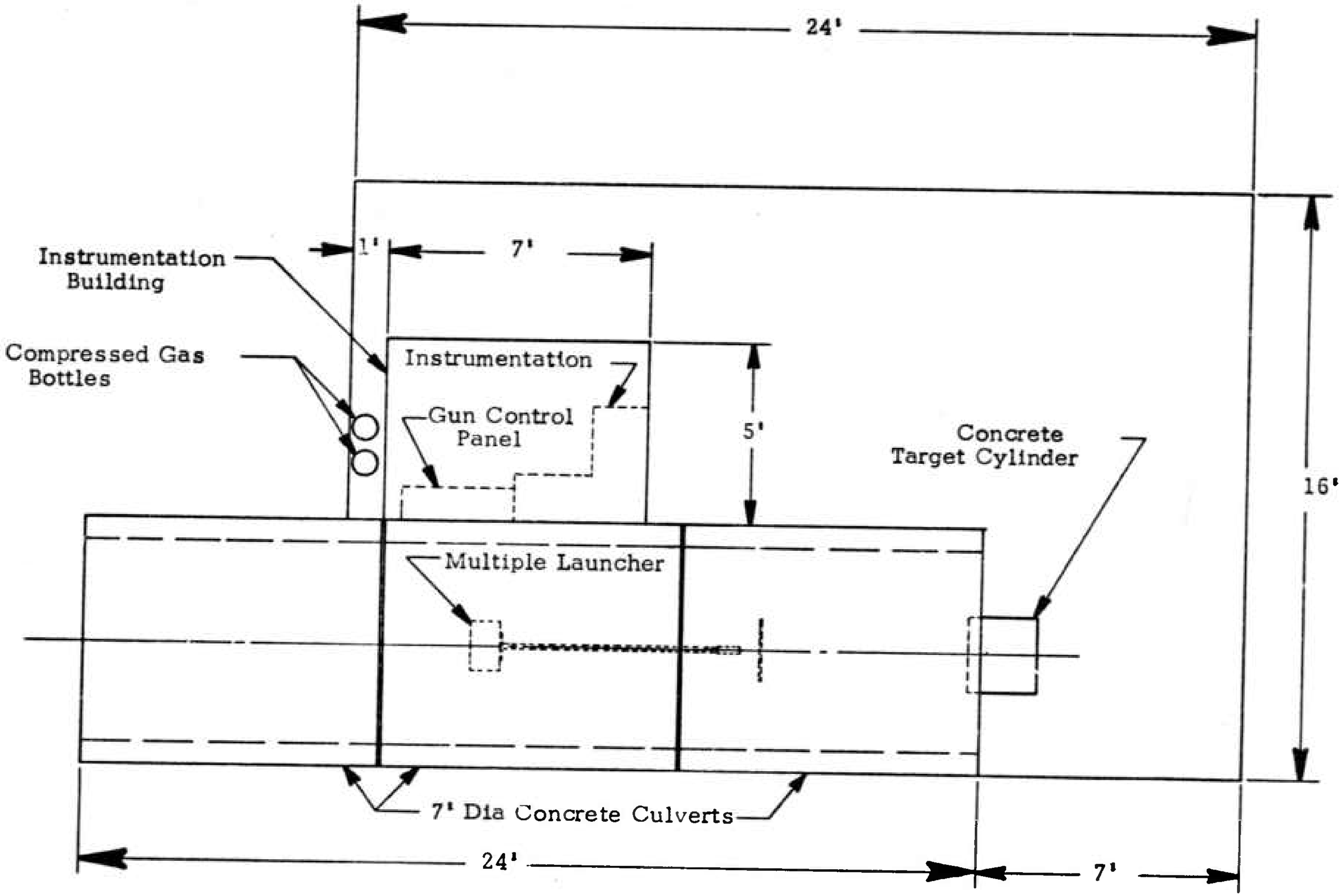

Figure 15 Multiple Launcher Facility

projectiles together would give an appreciable decrease in indicated velocity. The indicated velocity would differ even more from the nominal projectile velocity for groupings of more than two projectiles. The velocities obtained from the multiple launches were all very close to the nominal velocity for a single projectile.

In the unlikely event that spurious signals would be generated that exactly corresponded to the expected number of pulses and the nominal velocity, a further check was made by monitoring the pneumatic pressure surges generated as the projectiles were sequenced in the sequencer. Since these signals were derived from a pressure transducer system that is completely independent of the photo cell circuit, the correspondance between the two systems in time and number of pulses indicates that data from both systems were actual records of the projectiles being sequenced correctly by the launcher.

The time history of the sequenced projectiles is as follows. If the time at which the current to the firing solenoid valve is turned on, is regarded as zero time, the main gun valve opens at approximately .15 seconds. The first projectile is launched from the muzzle between .3 and .4 seconds after time zero. The second projectile exits from the muzzle from 30 to 60 millisecond after the first and the rest of the projectiles follow at fairly evenly spaced intervals of approximately 20 milliseconds. This value correcponds roughly to the calculated maximum firing rate of the launcher. A simple extension tube was designed and fabricated to permit up to 50 projectiles to be loaded behind the sequencer. However no tests have been run to see if the presently designed sequencer will sequence this many projectiles.

5. PROJECTILE STUDIES

5.1 PROJECTILE STABILITY

In multiple firings of explosive projectiles with the multiple launcher not all of the explosive projectiles detonated. The velocity of the projectiles in the train of projectiles was measured during the multiple launches and was found to be in the desired range of approximately 800 ft/sec. In view of this fact, it appeared that there were three principle causes for this occurance.

1. The detonators had somehow become less sensitive than they had previously been found to be.

2. There was aerodynamic tumbling of the projectiles so that many of them struck the target at the wrong angle to initiate detonation.

3. The blast from one projectile was such as to disturb the flight of a following projectile so that the projectile did not strike the target in an orientation required to cause detonation of the projectile.

To distinguish between these factors a series of single shot launches of explosive projectiles was fired. Since these were single shots, factor (3) would not be an active factor in any of the results of these firings. These single shot firings resulted in a large number of failures to detonate. Thus factors

(1) and (2) together or alone appeared to be responsible for the problem. Examination of projectiles that had not detonated showed that invariably the projectile had hit obliquely on the side or edge so that the detonator was partially shielded from impact. In view of this result, high speed framing sequences of a clay filled projectile fired from the launcher at a steel plate were made with a Dynafax camera. The framing sequences showed that the projectiles were not all striking the target flat on the end, as is necessary for actuation of the detonator.

Thus it appeared that it would be necessary to provide some stabilization of the projectiles in flight in order to provide the desired functioning of the multiple launcher.

Although, the interaction of one projectile with the blast of the previous one had not been entirely eliminated as a possible troublesome factor in the operation of the multiple launcher by these tests, it did not appear to be the most important factor. Further discussion of this appears in a following section.

Several methods were available to alleviate the misorientation of the projectile on impact of the target. One way was to lengthen the barrel and reduce the distance from the barrel to the target. This configuration would be similar to that of the single shot launcher used in the initial tests, where a high percentage of the projectiles detonated at impact.

The other way to handle the problem was to modify the launcher so that the projectiles fired from it would remain in the desired orientation over reasonable distances. This was the option that was chosen.

There are many ways to stabilize a projectile but it was desirable that stabilization be achieved by a method that would not alter the basic configuration and simplicity of the projectile itself. A stabilization method that would be acceptable was that of putting spin on the projectile. It was also desirable that minimum alteration to the basic design of the multiple launcher result from a spin stabilization modification.

A fixture to spin the projectile as it accelerates in the launcher was fabricated. It consisted of a 4-inch-long tube with shallow spiral rifling grooves on inside surface. Three sizes of fixtures were made, all with a slightly smaller I.D. than the barrel but large enough to pass the ordinary projectile. The three sizes differ by 1 mil on the I.D. from each other and were used to determine the effect of various engravements on the projectiles. There are 16 grooves in the rifled tube. These grooves were .074 wide and .008 deep, equally spaced around the circumference of the I.D. of the tube. The grooves had a 1/3 turn twist in the 4-inch length.

The design of the fixture was chosen from the configurations that could be obtained from a gun machine shop with a minimum of special tooling. Conventionally spin is obtained by the interaction of the rifling grooves with a soft metal portion of the projectile. However in this case, it seemed initially undesirable to cause distortion of the projectile case, if avoidable. Accordingly, the first design involved the interaction of the rifling grooves with a plastic

coating on the projectile. The requirements on the plastic coating were that it must be the correct thickness to engage the rifling grooves yet permit the projectile to slide easily down the regular launcher barrel. It must also adhere to the projectile and be strong enough to provide a strong rotating torque on the projectile as it passes through the rifling grooves. The rifled fixture was placed initially between the barrel and the accelerator tube.

Development of the plastic coating posed several problems, both in determining a workable type of plastic coating and in developing methods to apply the coating in a precise manner. The coating must be only a few mils thick.

To determine if the projectile were being spun by the grooves, a 12-inch-long by 1-inch-wide coil of #32 copper wire was placed longways beside the projectile path just when it exits the launcher. A bar magnet placed crosswise in the bottom of the projectile generates a signal when the projectile passes by the coil. This signal indicates whether the projectile is spinning.

The preliminary firings with inert projectiles indicated that the plastic coated projectiles were being spun while the uncoated were not. However, the presence of the restricted diameter rifled section near the breech gave slower than desired spins and projectile velocities. The launcher barrel was then machined to allow placement of the rifled section at the launcher muzzle. This resulted in improved spins and projectile velocities.

Although the magnet-coil arrangement showed that the projectiles were spinning, it could not show whether the projectiles were being stabilized. Confirmation of stabilization was obtained by examining the recovered projectiles after being fired in the launcher through the rifled fixture. A large number of inert projectiles were fired, some with slightly different plastic coatings, some with no coating but large enough in diameter to engage the rifling grooves. It was found that all the projectiles that were spun and launched at high velocity hit the target with the forward end of the projectile, as desired. It was also found that projectiles without a plastic coating but with the right increased case diameter could be spun with little distortion to the case, other than shallow impressions left by the rifling grooves, that did not affect the integrity of the casing.

A small number of explosive projectiles were fired singly, and it was found that all the projectiles that acquired high spin and velocity, detonated on impact with the target except for one projectile, which , although it hit squarely on the end and severely distorted the detonator casing, did not initiate the detonator. It is believed that this result was the exception, however, and generally satisfactory actuation of the detonator will occur.

A test with a string of six explosive projectiles was fired using casings without a plastic coating but large enough in diameter to engage the rifling grooves. All six detonators were actuated.

The limited scope of the program did not permit optimization of the spin stabilization solution to the hardware. However, the results of the preliminary test with the rifled fixture showed that this method is a workable method of stabilizing the projectiles.

5.2 MULTIPLE PROJECTILE INTERACTION

A study was made of the mechanisms that operate in closely-spaced pulsed explosions. If two pulsed explosions occur closely enough in time near the same point, then it is possible for the pressure wave from the second pulse to travel through material that is still being affected by the preceding wave. Analysis of the general conditions under which this could occur shows that the shock wave traveling through the granite will travel with, at least, the sound velocity i.e. greater than or equal to about 16,000 ft/sec or at least .19 inches/μsec. The pressure exerted by the detonation products is a small fraction of the compressive strength of granite approximately 60 μ secs after the explosion, so the next projectile must arrive within this time period in order for there to be appreciable interaction of the shock waves in the granite. Now if the projectiles are together when the first one detonates, then after detonation of the first projectile, if the second projectile does not detonate, it must move the distance of the first projectile plus the depth of the cavity produced by the first projectile, to strike the target surface. For granite this total distance is about .75 + .4 = 1.15 inches. To do this the projectile must travel at an average velocity of .019 inches/μsec or about 1600 ft/sec. However in this case, where they are so close together, the two projectiles are most likely to detonate together, so that the effect is that of a single projectile 3/4-inches in diameter and 1 1/2 inches long. It was shown in the section on explosive-rock interactions that single charges fired separately are more efficient in rock excavation than a composite charge with a mass equal to the sum of the masses of the single charges. Thus in this case, the efficiency of very closely spaced explosives is not likely to be more efficient than the case of separate explosive charges.

For charges that are somewhat farther apart, the problem of interference of the following projectile from the blast and debris of the preceding projectile is a serious problem. Dynafax pictures of the blast from a 3/4" x 3/4" C-4 projectile shows that the self-luminous portion of the blast traveling at over 6000 ft/sec, combining high temperatures with high pressures lasts about 60 μsecs. In addition, some portion of the 60 to 100 gms of removed rock or concrete is flying about. Such an environment may cause premature initiation of the detonator before it reaches the rock surface, or may disturb the orientation of the following projectile. Thus the 60 μsec time limit for interaction of the two shock waves makes exploitation of the close interaction of successive shock waves very difficult for realistic projectile velocities.

Now since very close interactions are not readily exploited, it is of interest to determine the time interval between successive projectiles for which the interference of a following projectile by the blast of the previous projectile will be small and negligible.

Figures 16 and 17 show the blast parameters of a typical 3/4" x 3/4" C-4 explosive projectile calculated from the explosive properties of the C-4 and scaled with respect the parameters measured in a TNT blast as reported in reference 6. As can be seen, by the time the blast has traveled 6 ft, ($\sim$4 milliseconds), its peak overpressure is only a few PSI and the positive pressure duration is less than .7 milliseconds. Thus, to be conservative, there should be negligible

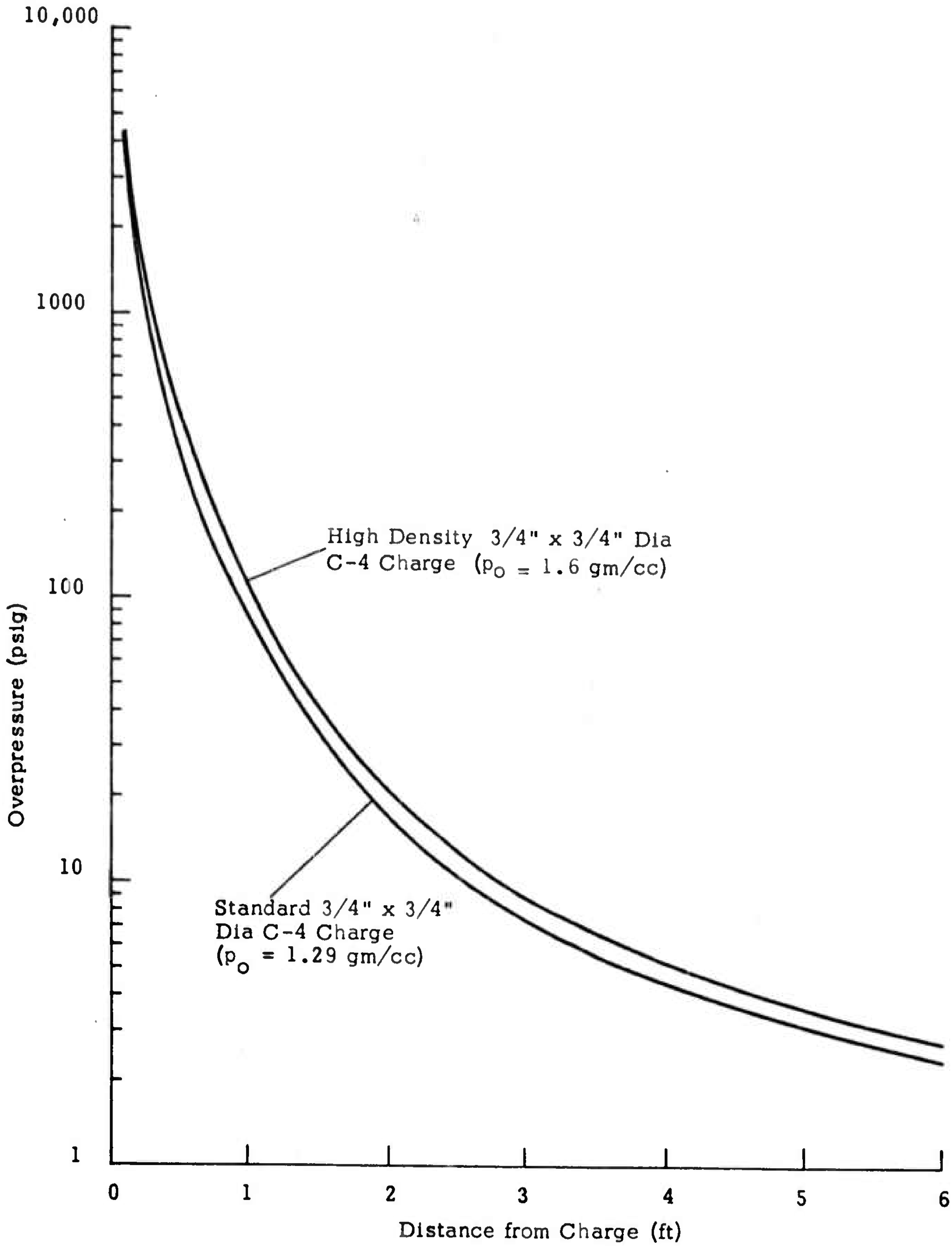

Figure 16 Blast Overpressure vs Blast Front Travel

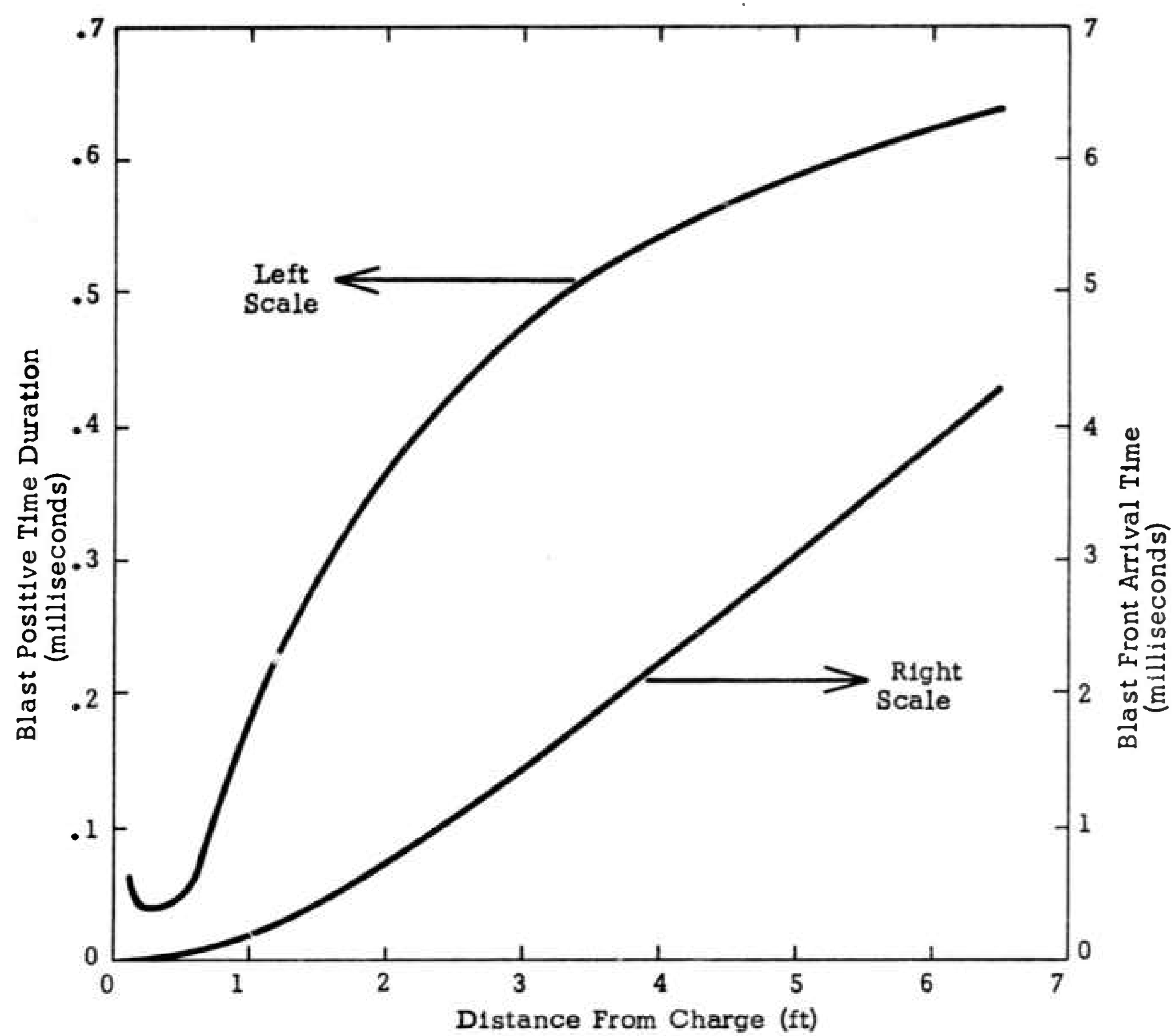

Figure 17 Positive Pressure Duration and Time of Blast Front Arrival vs Distance from Charge for a S:andard 3/4" x 3/4" C-4 Explosive Charge

blast interference with a following projectile if it reaches a point 10 ft from the rock target at a time 5 milliseconds after the explosion of previous projectile. This gives a minimum time between projectiles, for a projectile velocity of 800 ft/sec, of about 18 milliseconds. This time is very compatible with the firing speed of the prototype multiple launcher (20 millseconds between projectiles).

Besides blast, the following projectile must be exposed to minimum interference from the debris thrown out by the previous explosive. It should be noted that the debris is likely to be fine rock particles distributed over the entire solid angle over which the debris is discharged. The high speed dynafax pictures show that some debris is emitted over the entire 180° half sphere, with the debris in the center traveling about twice as fast as that on the sides. If, to be conservative, the debris is considered to be all distributed within a 15° solid angle cone, at 10 ft., the density of the 100 gms of rock particles will be approximately .027 gms/in^2 or about .012 gms over the frontal area of the projectile. Thus, at worst, the projectile will on the average collide with debris representing only .15% of its own mass. Even in the circumstance that the debris is traveling at twice the projectile velocity, the decrease in the projectile velocity from the momentum exchange is less than 10 ft/sec. The nature of the debris along the axis of the projectile flight, which it is most likely to encounter, was determined in an experiment in which a concrete cylinder resting on one side, with a horizontal cylindrical cavity approximately one foot deep, which had been explosively drilled by a series of projectiles from the launcher, was fitted with a horizontal 8 foot long steel tube. The tube had an inner diameter slightly larger than the explosively drilled hole and its opening was positioned over the opening of the hole. When a 3/4" x 3/4" C-4 charge was detonated against the concrete at the end of the hole, virtually all the debris found in the tube occurred between 1 and 2 feet into the tube. The debris consisted of pulverized rock somewhat finer than beach sand. Thus any debris striking the projectile would be of relatively small size (< 1mm in diameter) and traveling at a relatively low velocity for the projectile spacings obtained with the prototype multiple launcher.

As the precracking experiments showed, the interaction effects between successive projectiles seems to be minimal. While it would generally be expected that the generation of cracks in a material would make it much more susceptable to explosive attack, it should be noted that, contrary to bench type rock blasting where the rarefaction waves plays a predominant part, in crater type rock blasting, most of the rock must be pulverized through the action of the compressive portion of the shock wave. Thus the initial presence of even a large number of relatively widely distributed narrow cracks does not appear to affect the crater formation in a large expanse of rock.

6. EVALUATION AND RECOMMENDATIONS

It has been shown, in the preceeding sections, that the process of drilling into rock by the cratering mechanism can be characterized with regard to the critical parameters involved. The optimum conditions for drilling by a succession of small charges have been evaluated, and the construction of a multiple launcher capable of firing a succession of small explosive charges near the op-

timum conditions has been achieved.

The experimentally determined drilling speed of the system is very high and is over ten times the drilling speed of the most modern conventional methods. This represents a significant increase in the state of the art of rock drilling.

However, rock drilling is only one of several procedures required in the most efficient methods of large scale rock excavation. The most important of these other procedures involves cutting operations such as the cutting of a slot in a working face to generate a free surface area, and bench blasting where explosive packed into the drilled holes, generates a shock wave with the explosion, which reflects from the cut free surface area and breaks off a large portion of the working face. The use of bench blasting makes the explosive removal of rock very economical.

Since the multiple launcher is relatively light and maneuverable, it seems a reasonable possibility that a multiple launcher could cut a slot in a rock working face, drill holes in the working face, switch to a different explosive in the projectiles, then pack the hole with the right amount of correct explosive and then switch to a different projectile to detonate the explosive in the hole on a more or less continuous basis. This should provide very large increases in the advance rate compared to conventional rock excavation methods, while still obtaining the high explosive efficiency of the bench blasting technique.

Techniques of tunneling into rock on a continuous fashion have been devised in the past. One of these, patented by R.C. Baldwin in 1963, is particularly suited to use of the multiple launcher. In this technique, the working face is advanced in a spiral fashion around the axis of the tunnel, Figure 18. In such a geometry the free surface is continually generated along a radius from the axis. Thus it seems likely, with a judicious choice of impact point on the face, the explosives can drill into the face to achieve depth and also to react with the free surface, as with bench blasting, breaking off portions of the burden at the same time. This would give the speed of drilling and the efficiency of bench blasting in a single operation.

From the foregoing, it can be seen that the development of a rock excavation system incorporating the multiple launcher concept, promises the combination of exceptionally high speed and efficiency. The following recommendations are made as steps towards the attainment of this goal, taking into account that the basic concepts and prototype hardware have already been proven feasible.

(1) There should be a study on the mechanism of multiple charge drilling in rock next to a free surface parallel to the direction of drilling. This study should include consideration of the effects of charge size, hole size, depth and location relative to the free surface. Charge interaction effects should also be explored since for this geometry, precracking effects may be important.

(2) The launcher should be modified as necessary to prepare it for use in a specific type of excavation scheme and to prepare it to fire long trains of projectiles, which requires a continuous supply of high pressure gas.

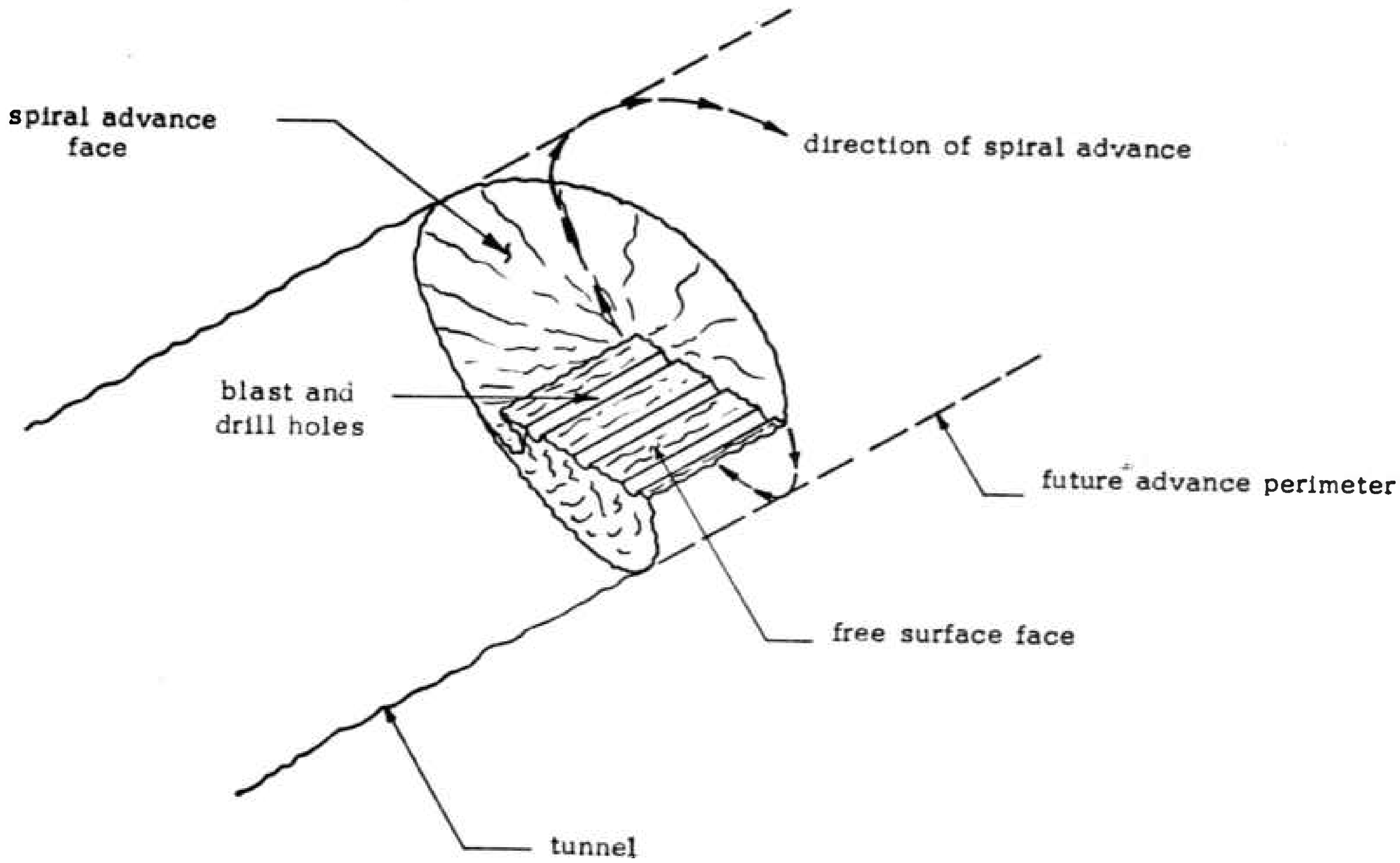

Figure 18. Continuous Spiral Tunneling Technique

(3) Actual use of the modified multiple launcher should be made under realistic conditions to investigate its performance under these conditions.

REFERENCES

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3. J.S. Rinehart, J. App. Phys., 22, Sept., 1951

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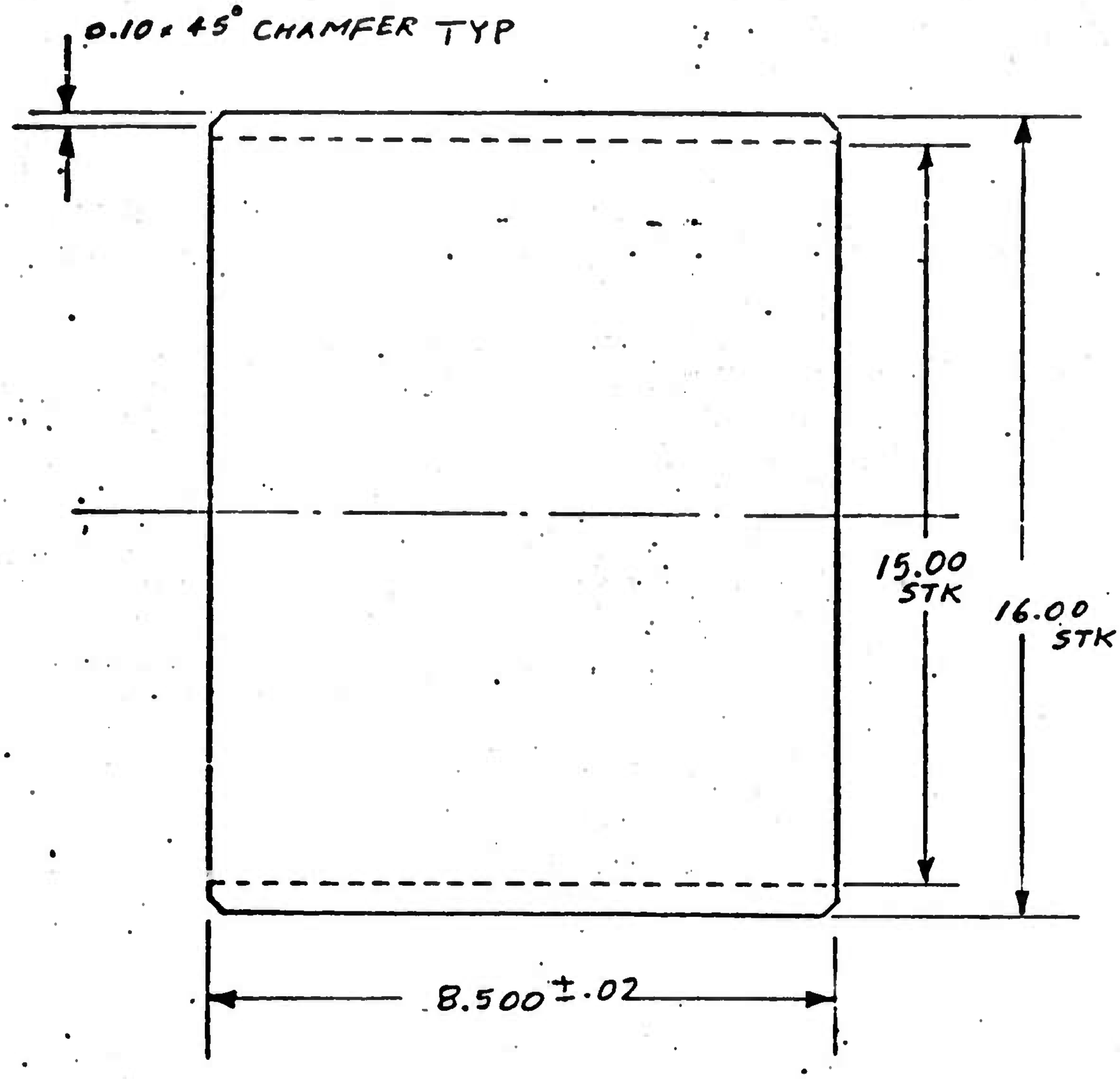
6. G.F. Kinney, Explosive Shocks in Air, Macmillan, New York, 1962

APPENDIX

1. Engineering Drawings of Multiple Launcher Components
2. Electronic Circuit

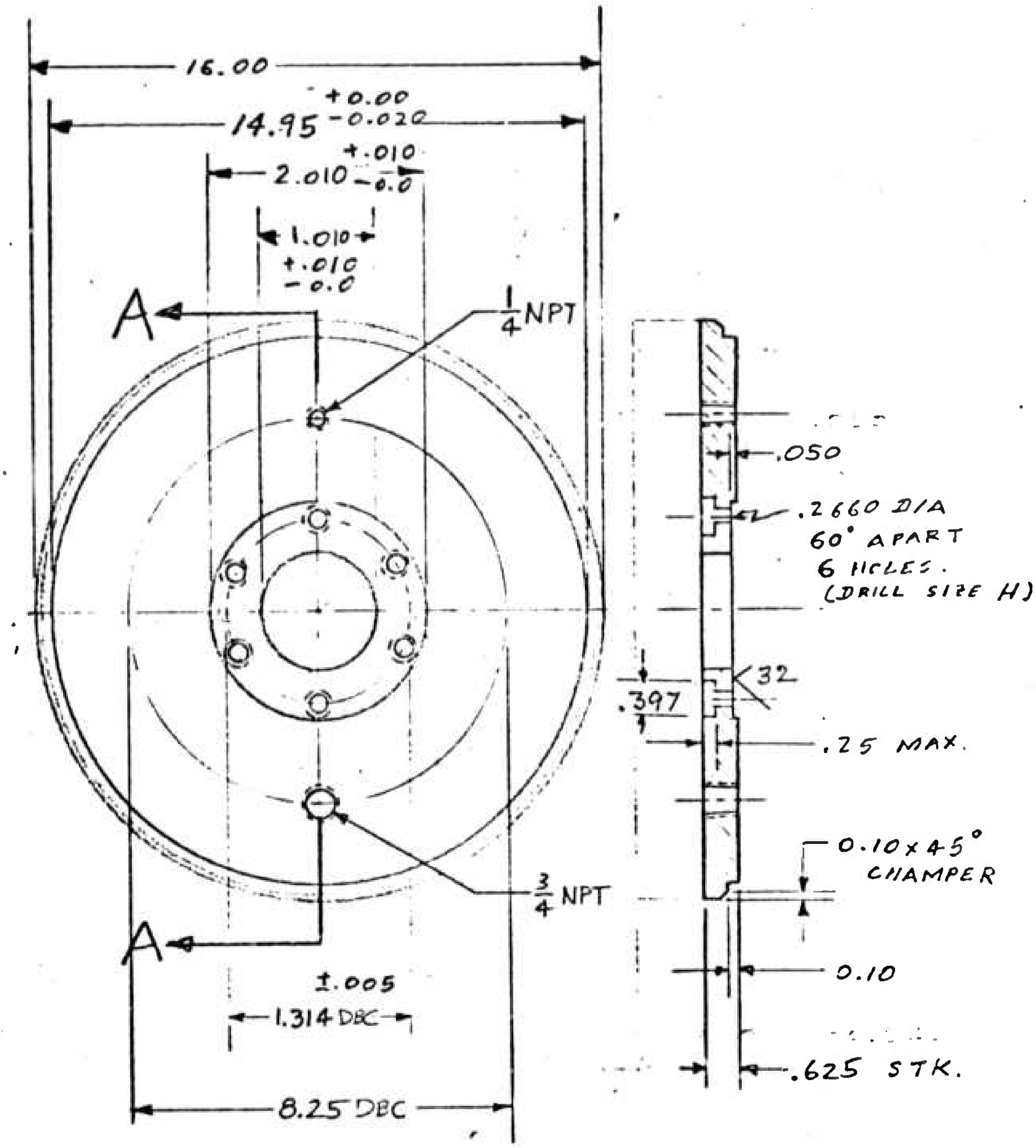


STEEL TUBE

MATERIAL SEAMLESS STEEL PIPE ASTM-A-53
35,000 PSI MIN. YIELD.

PART NO. 1

NOT TO SCALE



SECTION A-A

MATERIAL: 5/8" THK. STEEL PLATE
40,000 PSI MIN YIELD

PART NO. 2A

NOT TO SCALE

TOLERANCES
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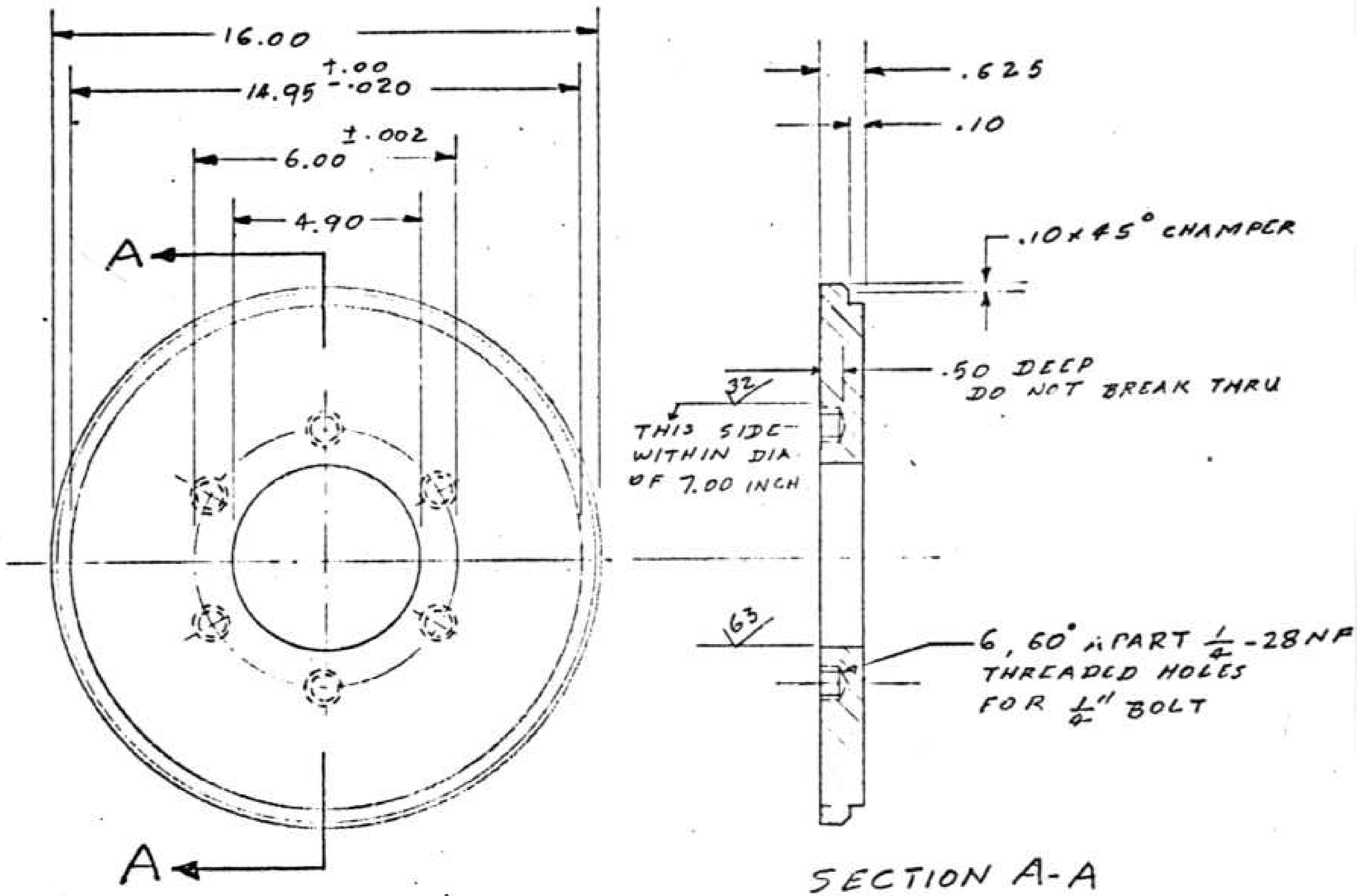
.XXX = ±.005
WHEN NOT GIVEN



MATERIAL: 5/8" THK. STEEL PLATE
40,000 PSI MIN YIELD.

TOLERANCES
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.XXX = ±.005
WHEN NOT GIVEN

PART NO. 2B

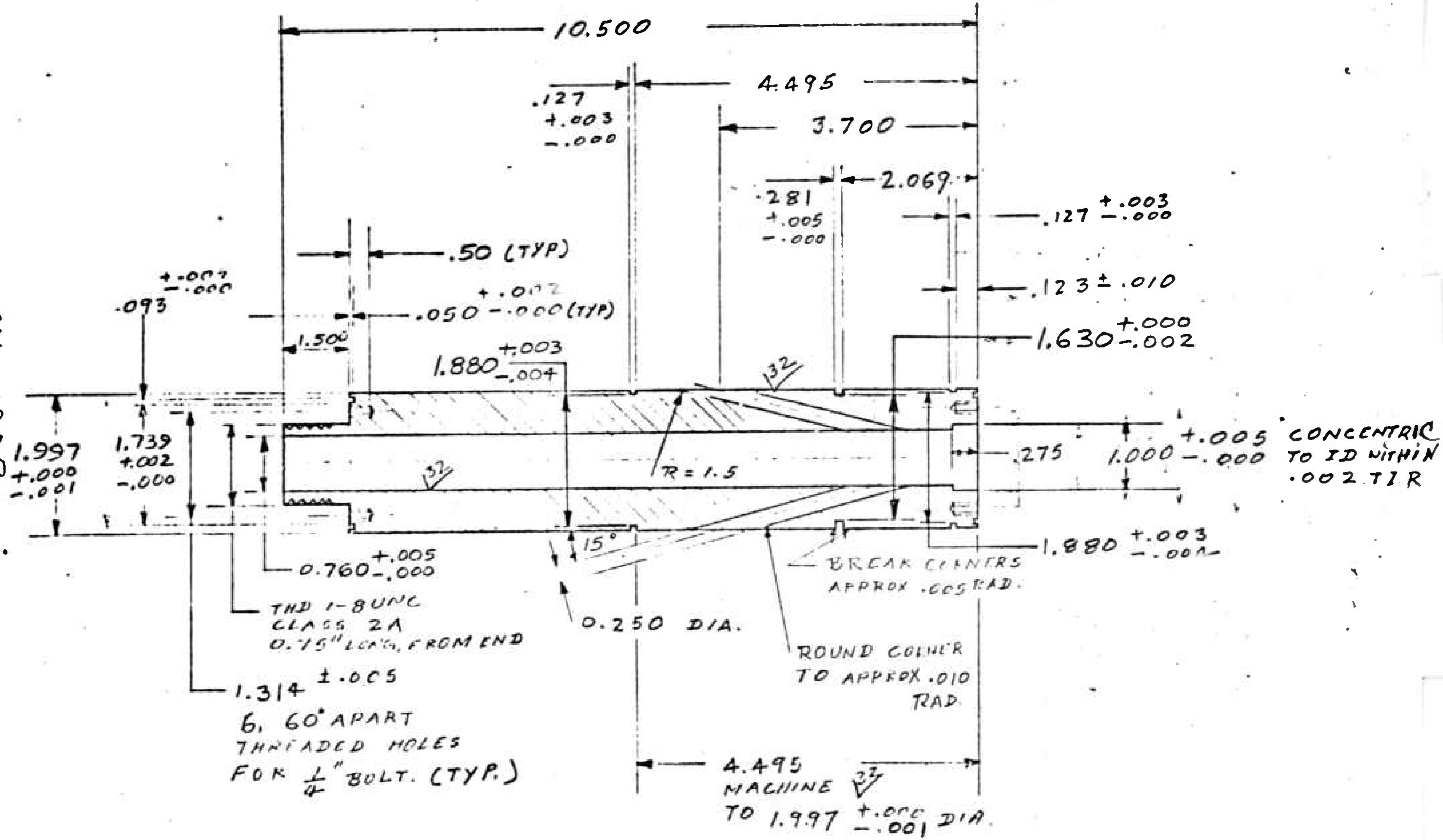
NOT TO SCALE

44 (Page complete)

PLATE

RS,JDD/HAL 9/2/72

C/H 117L(c)



MATERIAL: SHELBY SEAMLESS STEEL TUBING 2" O.D. x 3/4" WALL MINIMUM YIELD 50,000 PSI.

PART NO. 3.

NOT TO SCALE

TOLERANCES
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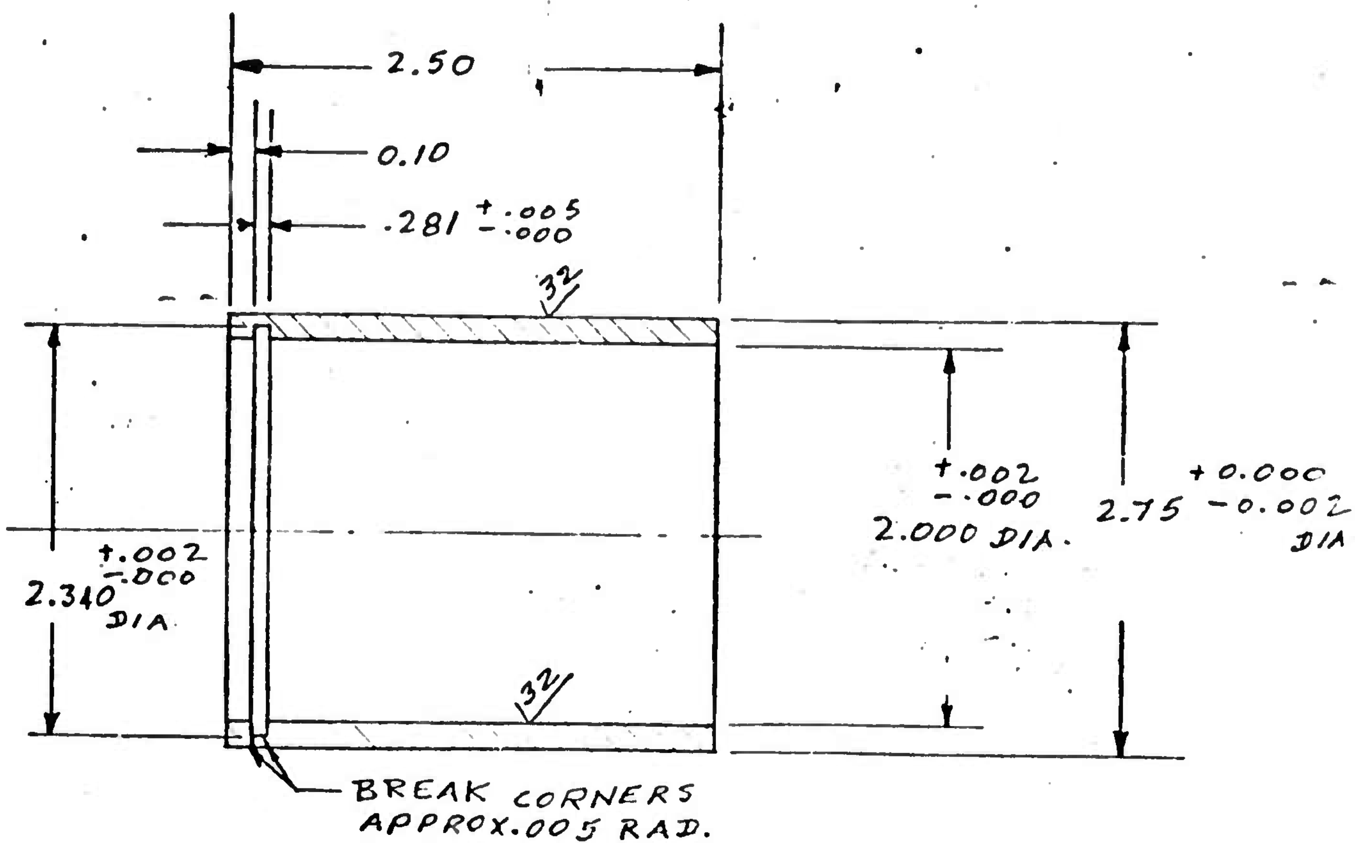
.XXX = .010
WHEN NOT GIVEN

45

CYLINDER

RS.JDD/mml 9/8/72

JU 1171(1)



WALL THICKNESS = 0.500", STOCK SIZE.
MATERIAL: 6061-T6 AL

2-329 O'RING.

PART NO - 4

NOT TO SCALE

TOLERANCES
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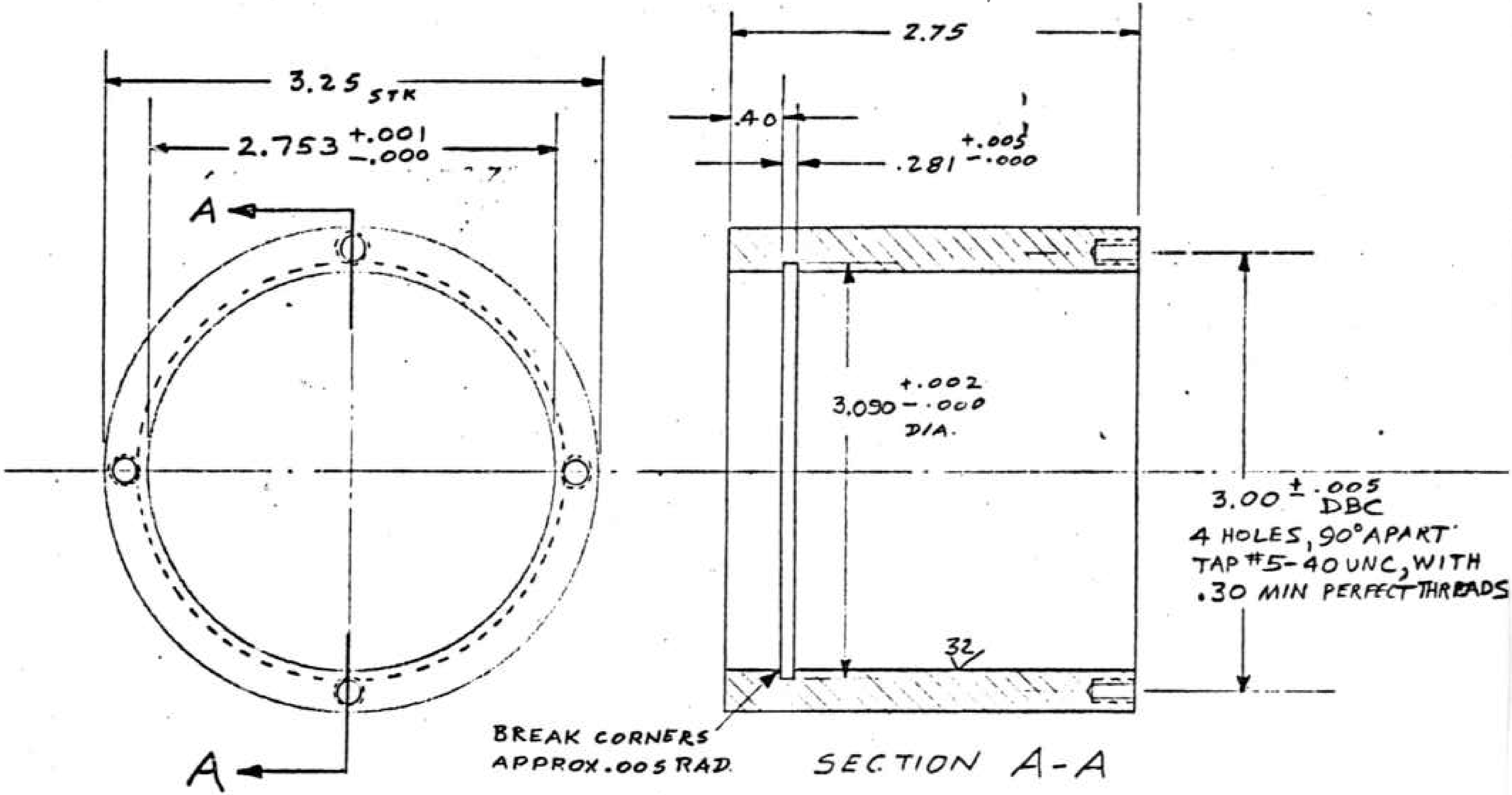
.XXX = ± .005
WHEN NOT GIVEN



MATERIAL: SHELBY SEAMLESS TUBING.

PART NO. 5
NOT TO SCALE

TOLERANCES
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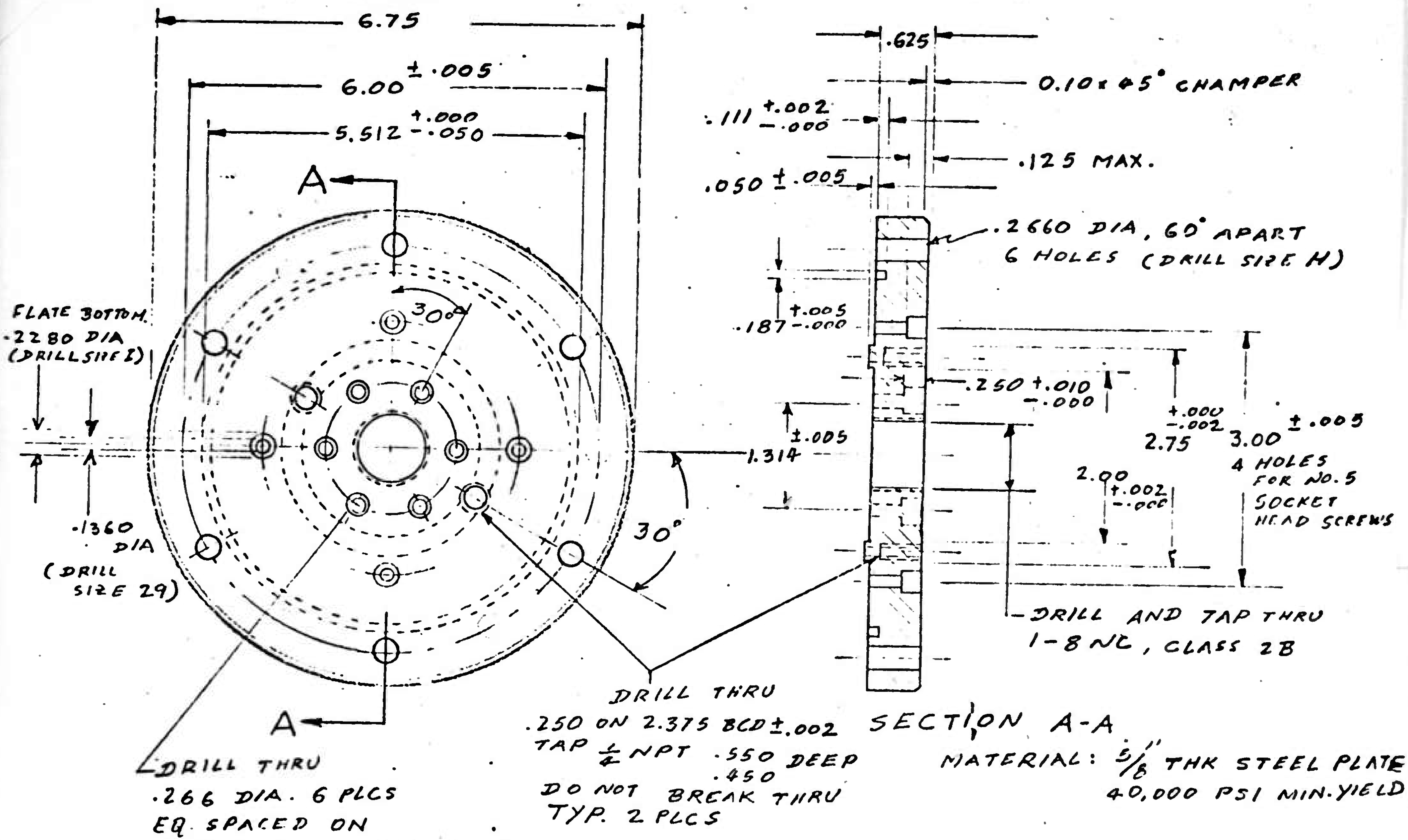
.XXX = ± .005
WHEN NOT GIVEN



MATERIAL: 5/8" THK STEEL PLATE
40,000 PSI MIN. YIELD

O'RING 2-252

TOLERANCES
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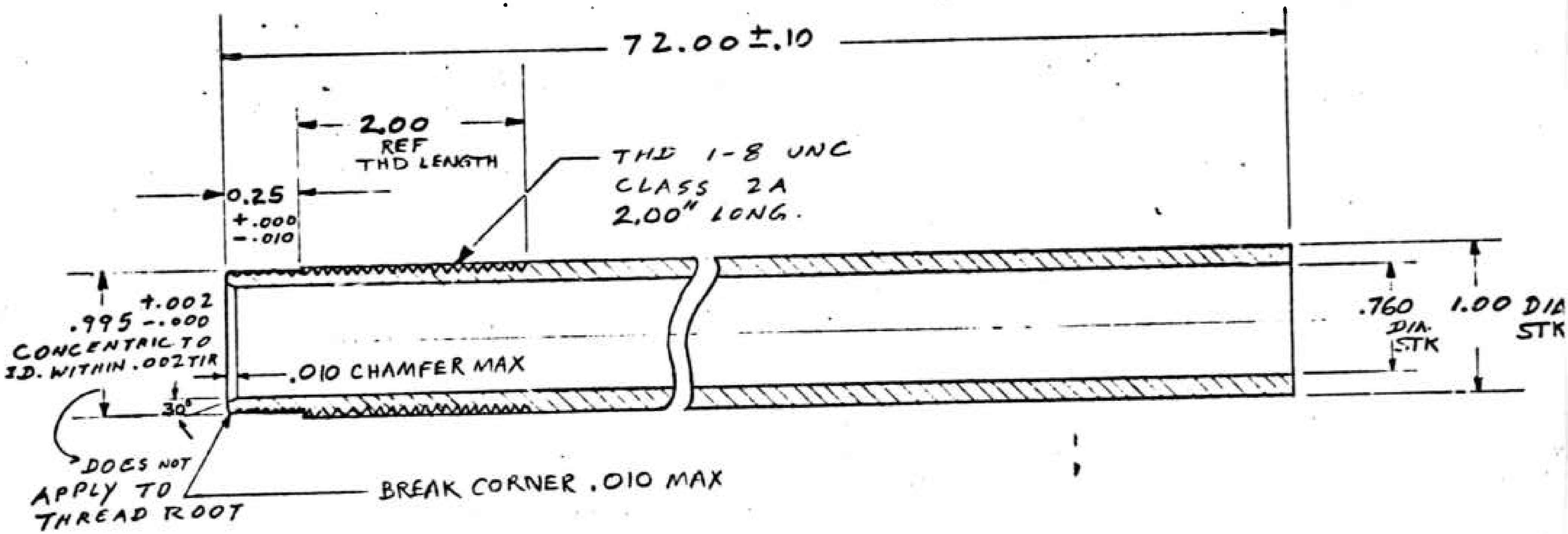
.XXX = ±.005
WHEN NOT GIVEN

PART NO. 6
NOT TO SCALE



MATERIAL: SHELBY SEAMLESS TUBING
1" O.D. X .120" WALL

TOLERANCES
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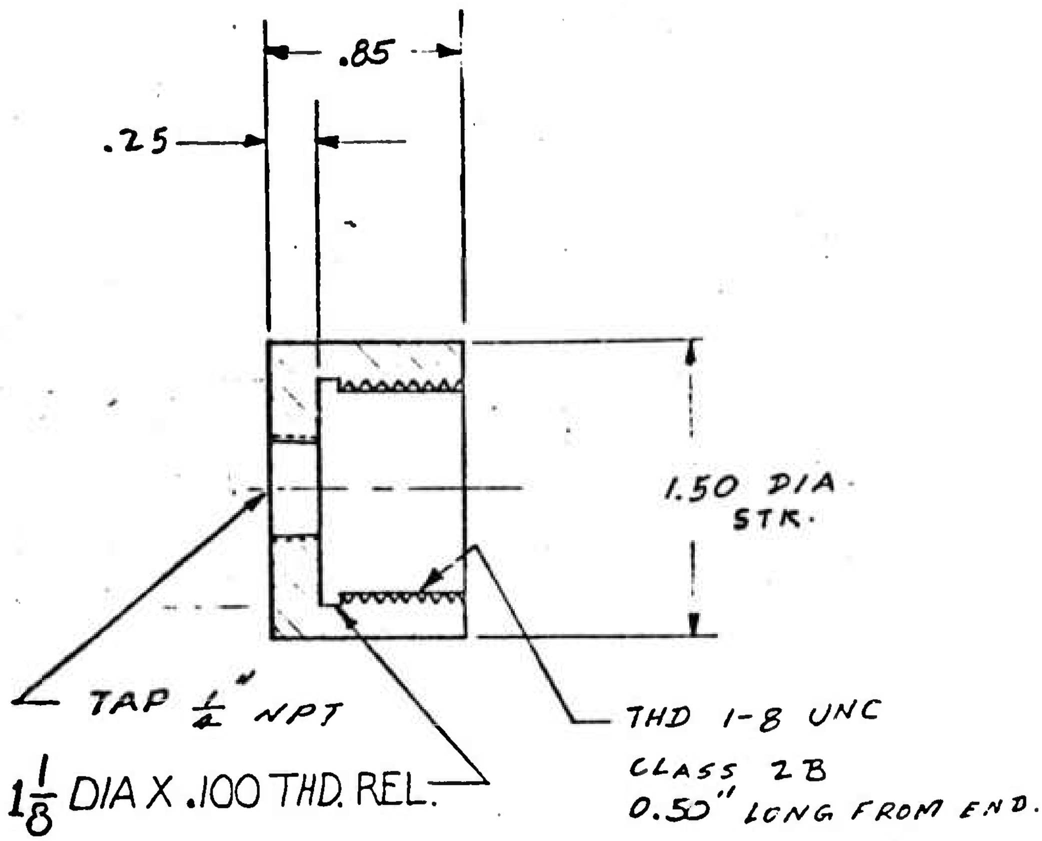
.XXX = ±.010
WHEN NOT GIVEN

PART NO. 7

NOT TO SCALE

49 (Page Complete)



MATERIAL: STEEL

PART NO. 8

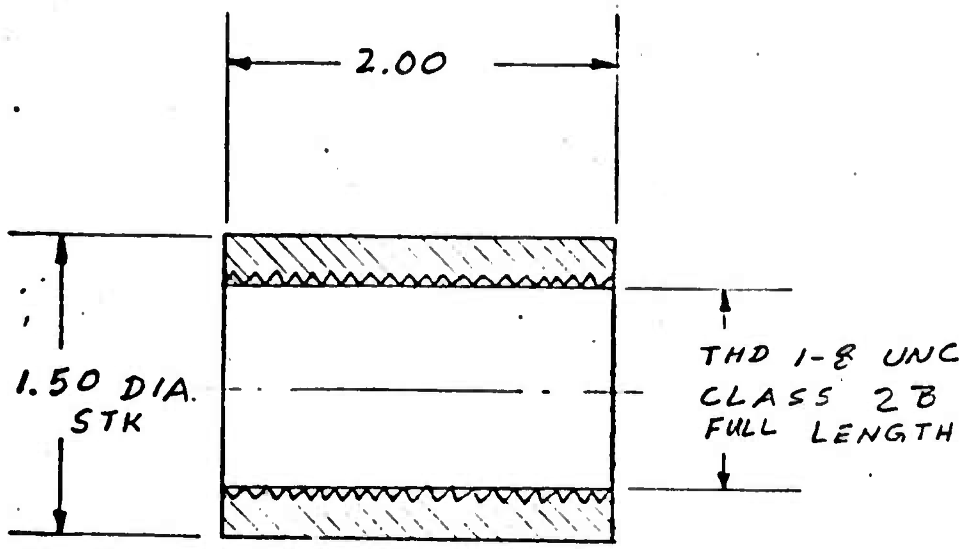
NOT TO SCALE

TOLERANCES

.XX = ± .050

.XXX = ± .010

WHEN NOT GIVEN



MATERIAL: STEEL

PART NO. 9

TOLERANCES
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WHEN NOT GIVEN

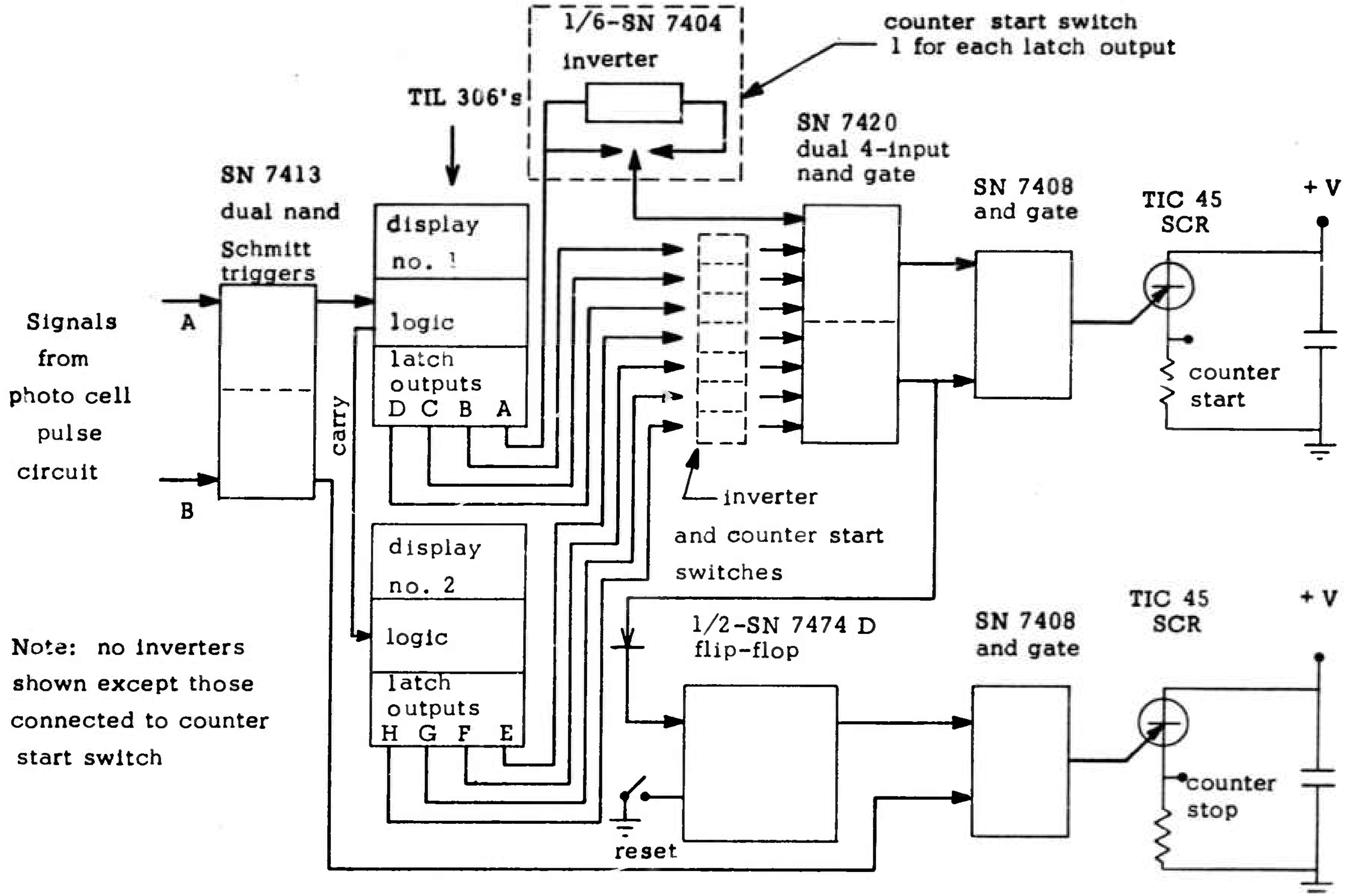

Figure A-2 Electronic Circuit